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# User's Manual for the Heat Pipe Space Radiator Design and Analysis Code (HEPSPARC)

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User Manual  
for the  
Multi-Purpose Heat Pipe Space Radiator  
Design and Analysis Code (HEPSPARC)  
Code Version 1.0

by

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Synopsis:

A new computer code has been written for the NASA Lewis Research Center named HEPSPARC (which stands for HEat Pipe SPace Radiator Code). This code is used for the design and analysis of a radiator that is constructed from a pumped fluid loop that transfers heat to the evaporative section of heat pipes.

This manual is designed to familiarize the user with this new code and to serve as a reference for its use. This manual documents the work done thus far. It is also intended to be the first step towards verification of the HEPSPARC code.

Details are furnished to provide a description of all the requirements and variables used in the design and analysis of a combined pumped loop/heat pipe radiator system. A description of the subroutines used in the program is furnished for those interested in understanding its detailed workings.



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## 1.0 GENERAL OVERVIEW:

### 1.1 INTRODUCTION:

The demand for increased spacecraft power brings with it a rise in waste heat rejection requirements due to power conversion system inefficiencies. This growth of power systems necessitates the ability to analyze the numerous radiator possibilities available to meet the requirements. The most efficient method to meet the specifications must be determined from the existing options. Thus, analytical modeling tools have become a requirement for power system heat transfer analysis, optimization, and comparison.

Existing spacecraft heat transfer systems are primarily composed of pumped loop systems (1), heat pipe systems (2), or combinations of the two, while advanced, low mass systems are also being developed (3,4,5) as alternatives. Current radiator designs show an increasing dependence on systems employing heat pipes. The growing dependency on heat pipes is in part due to the nearly isothermal character and high heat transfer capabilities inherent in the heat pipe concept. The increased dependence is also due to the fact that each heat pipe of a radiator system can be considered an independent entity. A designer can plan for heat pipe failures due to environmental hazards over the radiator life without concern for overall heat rejection system failure. Both these facts allow a heat pipe radiator to typically become lighter and smaller than a comparable pumped loop system.

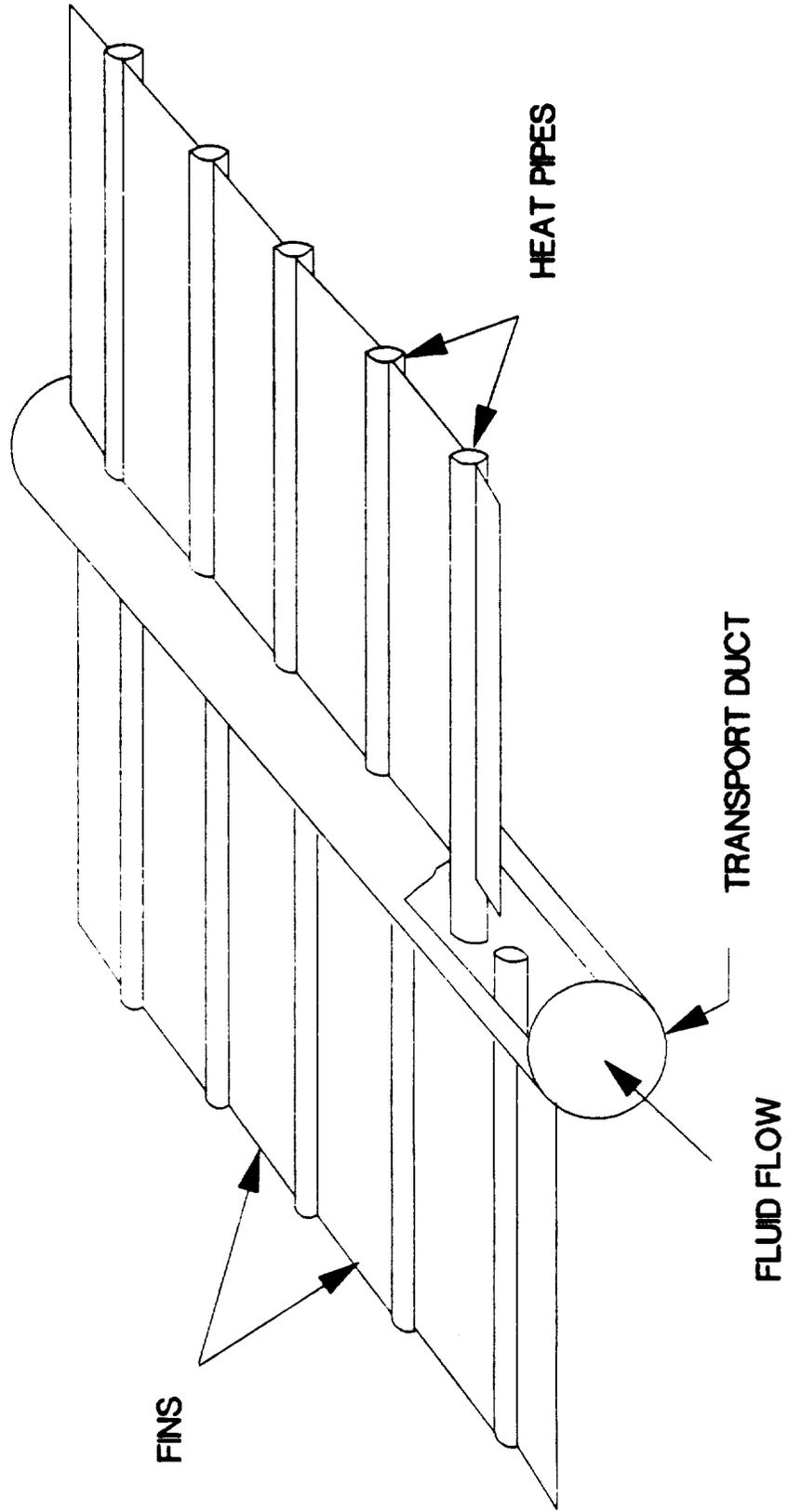
However, a radiator comprised strictly of heat pipes may have limited application due to complex power system/heat pipe interfaces. A combination of a pumped loop with heat pipes allows for greater heat rejection system versatility. Therefore, a new heat transfer analysis computer code has been developed for the NASA Lewis Research Center that analyzes a radiator comprised of a pumped fluid within a transport duct that moves across the evaporator section of a heat pipe array. Figure 1 depicts such a system.

### 1.2 CODE DESCRIPTION/USAGE

The new code can be used for numerous applications including the validation of contractor designs, in-house design and analysis efforts, and basic conceptual analyses. It is designed to allow maximum versatility and is capable of, but not limited to the analysis of radiator systems for Stirling and Brayton engines, thermoelectric elements, and terrestrial, planetary, and orbital situations.

The code's radiator analysis allows two options. A detailed thermal analysis that determines the overall radiator characteristics, or an option that determines a minimum mass radiator. In the latter, a specific parameter is varied for the optimization. The program then iterates within specified limits until the minimum mass configuration is determined. The specific working fluid within a heat pipe only allows operation in certain temperature ranges and pressures. Therefore, the code has been written in such a way that only applicable working fluids can be used at certain temperature levels. When

FIGURE 1: BASIC RADIATOR DESIGN CONFIGURATION



the radiator must produce a large temperature change in the pumped loop fluid, the code indexes through different heat pipes chosen for the design. The temperature of a particular heat pipe is checked against specified limits to determine its acceptability at a particular radiator location. If the heat pipe is found to be operating at or over a limit, a heat pipe with a different working fluid will be chosen. This capability allows the program to be used for the design and analysis of radiators that require a large temperature drop in the transport duct fluid. A radiator for a Brayton cycle system presents such a situation. The optimization option also accounts for multiple heat pipe types in its calculations and allows independent optimizing calculations of each heat pipe type to minimize the entire radiator mass.

One of the most important aspects of a design for a space based radiator system is the manner in which it is protected from the space environment. The protection method used is referred to as armoring or bumpering. The determination of the required armoring in the code follows the methodology described in Reference (6). It uses an iterative technique to balance the number of allowable losses of heat pipes or transport ducts with that predicted by an assumed armor thickness using a "critical particle flux". Particle impact effects are accounted for by the choice of two models: the NASA thick plate, with specified adjustment factors (7,8), or the NASA thin plate model (8). Armoring thickness is adjusted until the design specified number of heat pipe losses is at its maximum allowable value. This technique allows the analyst to account for the radiator environmental conditions. It also allows a reduced mass design by use of redundancy in the heat pipes as well as with the transport ducts. Additional program options will allow the use of offset bumpering as transport duct protection.

### 1.3      CODE HIGHLIGHTS/DETAIL:

The complexity and generality of this program causes its input to be detailed. Table 1 summarizes the input and user options available. An adequate knowledge of heat pipes is needed to specify all the required parameters. Basic understanding of space radiator design is also necessary to make maximum use of the program. A significant amount of detail about the radiator is returned from the code analysis (see Table 2). When the optimization option is used, information about the iterative step values is also output in order to track the minimization process.

The code offers many unique features. A built-in library offers the designer a wide selection of radiator materials. The option of using properties not already in the library by allowing user defined properties is also available. This allows a designer to easily determine the relative impact of new materials on a radiator design. Data is also available within the program to indicate known compatibility information between the materials chosen for use.

Other program features include the use of fin and heat pipe efficiencies. This accounts for the non-isothermal fin conditions as well as radiation interchange between the fins and adjacent heat pipes.

# TABLE 1: INPUTS AND USER OPTIONS

- INPUTS:
  - HEAT TRANSFER REQUIREMENTS
  - TEMPERATURES
    - INLET, OUTLET & SINK
  - PRESSURES
  - SURVIVABILITY INFORMATION
  - SPACECRAFT ALTITUDE
  - VIEW FACTORS AND EMISSIVITIES
  - ALL HEAT PIPE CHARACTERISTICS
  - ARMORING AND LINER MATERIAL CHOICES
  
- OPTIONS:
  - TRANSPORT DUCT CONFIGURATIONS
    - HEAT PIPES IN DUCT
    - HEAT PIPES ON DUCT
    - HEAT PIPES ON ONE OR BOTH SIDES OF DUCT
  - ARMORING OPTIONS
    - NASA THIN PLATE
    - NASA THICK PLATE WITH SPECIFIED CORRECTION FACTOR
    - BUMPERING
  - ENVIRONMENTAL OPTIONS
    - SPACE DEBRIS/MICROMETEOROD COMBINATIONS
    - EXTERNAL CONVECTIVE COEFFICIENTS
  - SUPPLEMENTAL MASS ADDITIONS
  - RADIATOR SPACE CONSTRAINT SITUATIONS

## TABLE 2: HEPSPARC OUTPUT

INPUT REITERATION

SYSTEM DESCRIPTION

MATERIAL THICKNESS DETERMINATION

FLUID/MATERIALS COMPATIBILITIES

HEAT PIPE LIMIT VIOLATION NOTICE

SIZES

NUMBER OF HEAT PIPES (BROKEN INTO SPECIFIC TYPES)

MASS BREAKDOWNS

SIMPLE STRESS BREAKDOWNS

SPECIFIC MASS AND SPECIFIC POWER VALUES

BEGINNING AND END OF MISSION CHARACTERISTICS

Any radiator geometry is easily modeled by using specified input and options available. The basic configurations analyzed thus far include a simple flat plate design, a cylindrical shape, and a conical shape. Each of these configurations still allow for the use of all the program options previously mentioned.

The basic structure of the radiator code's heat pipe analysis section is based on portions of the NASA Lewis Heat Pipe Code (9). The technique employed for evaluation of the heat pipe characteristics is an iterative method of determining the thermal resistance and temperatures of the various sections of the heat pipe. Essentially, a one-dimensional, lumped parameter, thermal network model is used to obtain the heat transfer characteristics of the heat pipes. Heat transfer limits are checked using fundamental equations available in the literature.

The Lewis Heat Pipe Code allows for the use of a wide variety of heat pipe wick structures. The choices available include wrapped screens, with or without arteries, sintered metals, with or without arteries, and grooves. An option also exists that allows the user to define all the parameters needed for the thermal calculations. This provides the flexibility required to evaluate new or different heat pipe concepts.

#### 1.4            PURPOSE OF THIS MANUAL

The new code, named HEPSPARC, for HEat Pipe SPace Radiator Code, is very generic in nature and allows for the design and analysis of a combined heat pipe/pumped loop radiator for a wide variety of situations. This user manual describes the usage, capabilities, and structure of this code. Details of all aspects of the code will be described. Sufficient input requirements and specifications will be provided to supply information to allow a new user to work with the program.

This document allows users of various interest levels to pinpoint the sections they may wish to read. As already seen, Section 1 has provided basic overall description of the code and its application. Basic material involved with the workings of the program is furnished in Section 2, while Section 3 details the requirements for actual usage of the code. Section 4 provides information for understanding the code output as well as additional basic information for its usage. Section 5 provides some final instructions and guidance for the user. Section 6 contains (in the original version of this manual only) a floppy disk with a copy of the program along with a description of the subroutines involved in the code. Section 7 contains the list of references for this document.

## 2.0 CODE DETAILS:

This section of the user manual describes the basic calculation methods employed in HEPSPARC. Detailed equations, methods, and procedures are furnished to help describe, document, and justify the workings of this radiator design code. Details of the structure, models, and layout of HEPSPARC are furnished.

### 2.1 GENERAL:

As mentioned previously, the program is designed to be generic in nature. Therefore, much is left up to the designer and his or her understanding of the code. Sufficient flexibility exists to handle a great many situations that may arise. However, as with any computer code, the scope of possibilities addressed has to be limited.

#### 2.1.1 Operating System

The code is currently limited to a VAX computer system. This does not necessarily mean that it can not be placed on other machines. However, in its current form, the code makes use of an IMSL (Integrated Math Subroutine Library) subroutine which is present on the NASA Lewis VAX system. Specifically, the function used is entitled DPOID. It evaluates the value of a Poisson distribution for the armor thickness calculations. Any transfer of the HEPSPARC program to a different system would have to account for this use of the IMSL function. Additionally, the use of this program on a personal computer is not recommended at this time. Work is still required on the code in order to make its operation more efficient. Certain calculations currently used in the code make it more adaptive to a mainframe machine. Until work can be done to optimize the actual workings of the code, any attempted use on a personal computer may prove frustrating to a user.

#### 2.1.2 Basic Procedures

This code is used for the design of a heat rejection radiator system, primarily for space applications comprised of pumped fluid loop that transports heat from a heat source to the evaporative section of heat pipes. The pumped fluid can be either a liquid or a vapor with the allowance for phase change to occur in the loop. The heat pipes are devices that use the latent heat of a fluid to transport heat from one point to another. Fluid evaporates from the evaporative section of a heat pipe's wick structure and is carried down the pipe by hydrodynamic forces until it reaches the condensing section. At that point, the vapor condenses, thereby giving up its latent heat which is radiated to space from the outside surfaces of the heat pipes. The fluid from the condenser is then returned to the evaporator section via capillary action in the wick structure and the process starts over.

## Heat Transfer

The heat pipes act as the primary location at which heat is rejected from the system. The pumped fluid loop is contained within what is referred to as a transport duct or header. This also rejects heat, but its contribution to the overall system heat transfer capabilities is typically small when compared to that of the heat pipes. For space applications, the heat transfer occurs by radiation exchange with the environment. An option exists for specifying a convective coefficient for the external surfaces of a radiator. This was added to allow the code to model terrestrial applications.

The code allows for two types of computational design options. The first option allows one to specify the radiator design. The second option allows for the code to produce a design that has a minimum mass. For the first, all the basic characteristics of the radiator are specified. The size of the transport duct as well as all the characteristics of the heat pipes are known. This type of analysis is used as an analytic tool rather than a design tool. It can help determine the performance of an existing radiator design. It allows itself to be used specifically for the verification of the size and performance of previously designed radiator systems.

In this case, the heat transfer of the system is specified as well as the required temperature change of the transport duct fluid. The temperature of this duct fluid establishes the fluids that may be used in the system heat pipes. This method of analysis follows the transport duct fluid through the radiator. Each heat pipe is analyzed for its heat transfer capabilities. The amount of heat transferred is then associated with the temperature change experienced by the flowing fluid using the simple relation:

$$Q = mc_p\Delta T$$

This process continues with more heat pipes being added until either the total heat transfer of the system is met, or the temperature of the transport duct fluid is such that a different heat pipe fluid is required. In the latter case, the analysis proceeds in the same manner and continues to index through the user specified heat pipe fluids until the required heat transfer of the system is met. The calculated number of each type of heat pipe ("type" here refers to a heat pipe that utilizes a different working fluid) is the minimum required that must survive the entire mission duration. This value is coupled with the armoring calculations (described below) and specified redundancy to determine material thicknesses. Variation in the armoring thickness has an effect on the heat transfer calculations, and therefore, the process is iterative in nature in order to determine the final radiator performance. It should be noted that the heat transfer of the transport duct itself is also included in the determination of the overall system heat transfer capabilities.

The second method available is for the design of a radiator to meet specific mission needs. With this, one of five possible radiator characteristics is to be varied to obtain a minimum mass radiator system design. Currently, the variables available for optimization include the system redundancy (for both the heat pipes as well as the transport ducts),

heat pipe diameter (and as this variable changes, the internal thermal-hydraulic characteristics of the heat pipe also change), fin width (defined as the physical spacing between the heat pipes), and fin thickness. The latter three variables can be optimized for each type of heat pipe used in the radiator system. To allow for the additional calculations in the optimization analysis to occur in a timely manner (i.e. the basic mass comparison of several different radiator designs), each individual heat pipe is not examined. Rather, a representative heat pipe is chosen for a section of the radiator transport duct fluid that undergoes a specified temperature change. An estimate of the number of heat pipes needed for the heat transfer of the radiator section is determined. As before, this continues until either the specified heat transfer of the system is met, or a new heat pipe working fluid is required. Also as before, the number of heat pipes determined is used in an iterative manner with the armor thickness calculations. The transport duct heat transfer is also included in the optimization analysis. With the variables available for optimization, a radiator design can be progressively refined in order to obtain the overall optimal design configuration. It may be suggested that when this is complete, the simple mass determination mode of the program may be used to verify the results from the optimization algorithm. It is desired to expand this section of the program substantially. First, the addition of heat pipe length as an optimization variable is desired. Then, the program could examine all the optimization variables itself to determine the final design. This would significantly reduce the amount of user interaction required by the program but would prove to be a formidable programming task.

### Basic Armoring Methodology

Radiators in orbit around the Earth are exposed to an environment of micro-meteoroids and space debris particles. These objects, though typically very small, may be travelling at velocities in excess of 20 km/s. Upon contact with a radiator surface, there is often sufficient energy transferred to puncture the material. If the puncture occurs at a location that is a fluid boundary, the fluid is lost to space and the radiator area that was serviced by the fluid becomes ineffective. Therefore, the design of space radiators must accommodate the effects of this environment.

The material used in a radiator system protects it from the space environment. When the radiator material is used to protect the underlying objects, such as a fluid boundary, it is referred to as armoring or bumpering, depending on the application of protection methods (this area will be addressed in more detail later in this document). To prevent all punctures of a system, the armor must be made very thick. This results in a heavy radiator design. Redundancy, as described above, can reduce the mass of a radiator. Some components may become inoperative due to the punctures that may occur, but the radiator still is able to function due to the excess number of components. The result of using redundancy is that the armoring of the components becomes significantly less, and an overall radiator system is less massive.

Heat pipes represent components that are generally small in size that

operate independently from one another. Heat pipes can operate in parallel with one another providing redundancy in a system. This redundancy can be used both for a pumped loop and heat pipe radiator design. The code allows for the design of a radiator that is comprised of a number of independently pumped loops, or transport ducts, that are coupled to their own set of heat pipes (see Figure 2). Thus, it is possible for the designer to allow the transport ducts to have "extras" as well as to have redundant heat pipes attached to them. Both of these variables are options that exist for the mass minimization design in the code.

### 2.1.3            GENERAL FLOW CHART

The code is broken down into two main sections. These are the mass minimizing use of the code (referred to as the optimizing method) and the basic code use (referred to as the non-optimizing method). These make use of a number of common subsections for their calculation purposes. These include input and output sections, heat pipe and transport duct heat transfer calculations, materials data, armor determination, material compatibility checking, stress analysis, and pressure drop calculations.

The flow chart of the operation of HEPSPARC showing the control structure and basic interaction with the various subsections is shown in Figures 3 and 4 for the optimized and non-optimized cases respectively. More detailed information pertaining to calculational methods will follow as each of the various program sections is described. The sections are each made up of several subroutines. The purpose of each subroutine (listed by name) is given in section 6.1 for reference.

### 2.1.4            DESCRIPTION OF CODE WORKINGS

The following sections describe the logic and course followed in the operation of the code. The information given is an expansion of the flow chart presented previously. It furnishes information about the intricate workings of the code for those who are interested or require this level of detail.

#### 2.1.4.1        NON-OPTIMIZED METHOD

The first step taken in the design/analysis of a combined heat pipe/pumped loop radiator is to estimate of the number of heat pipes required to transfer the specified amount of heat. This value is based on an end of life mission requirement that needs to be met and would be part of the basic design specification. The total heat transfer required is divided by the number of independent transport ducts that are specified to survive for the mission. The analysis proceeds, concentrating on the design of one transport duct and its heat pipes and then uses symmetry to determine the overall radiator design.

A representative radiator temperature is chosen and the heat that one

**FIGURE 2: BASIC DESCRIPTION OF RADIATOR SYSTEM**

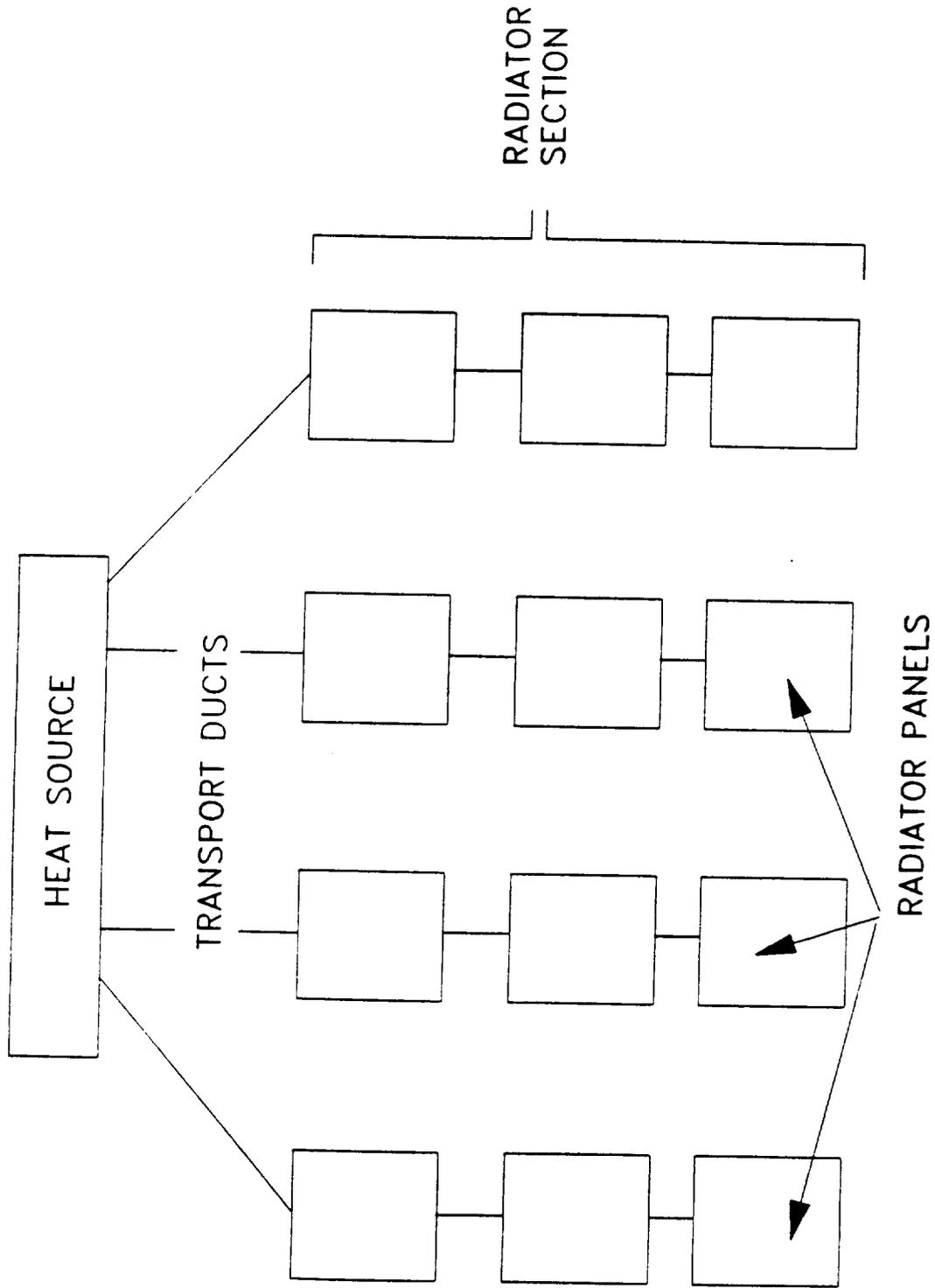


FIGURE 3: NON-OPTIMIZED FLOW CHART

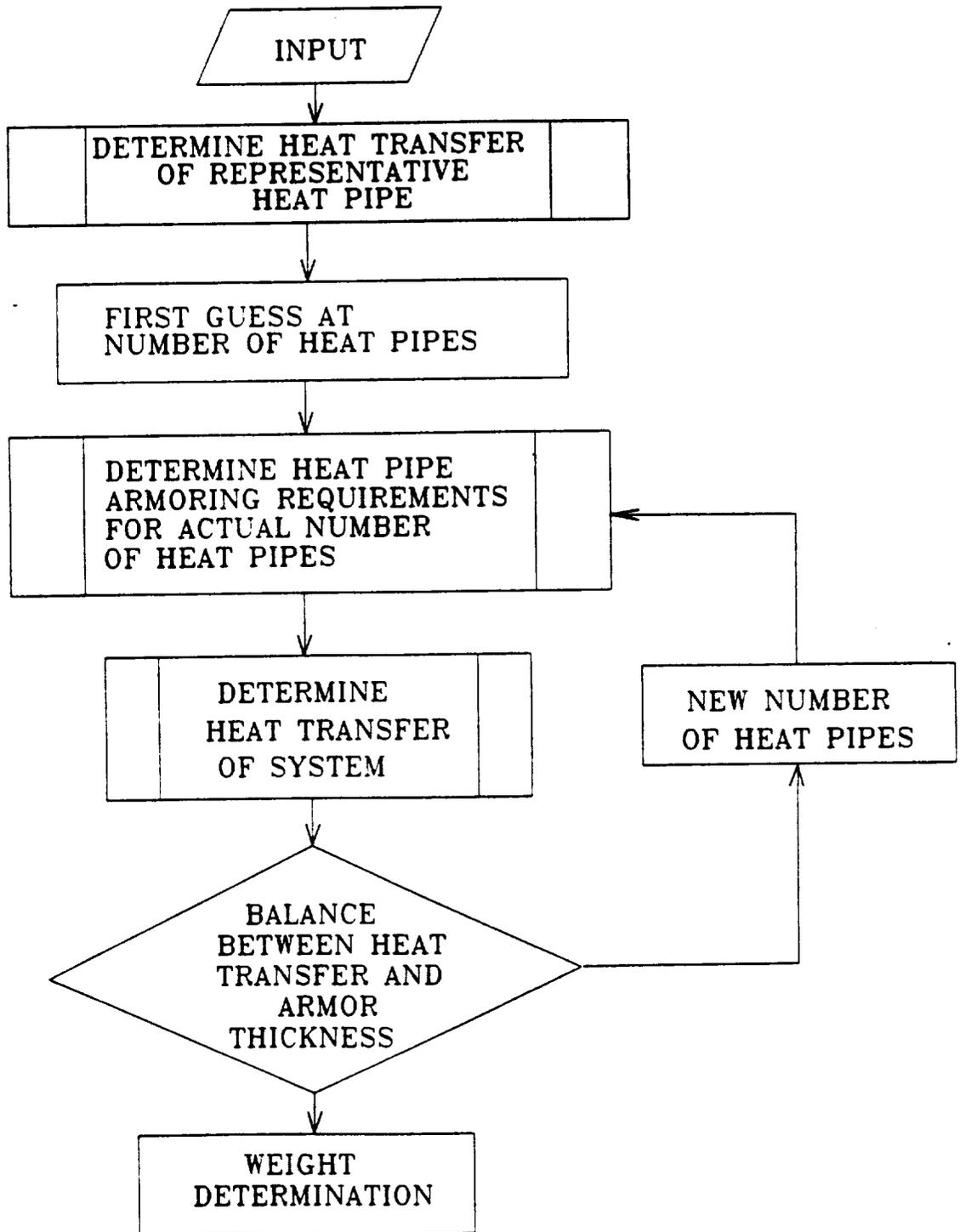
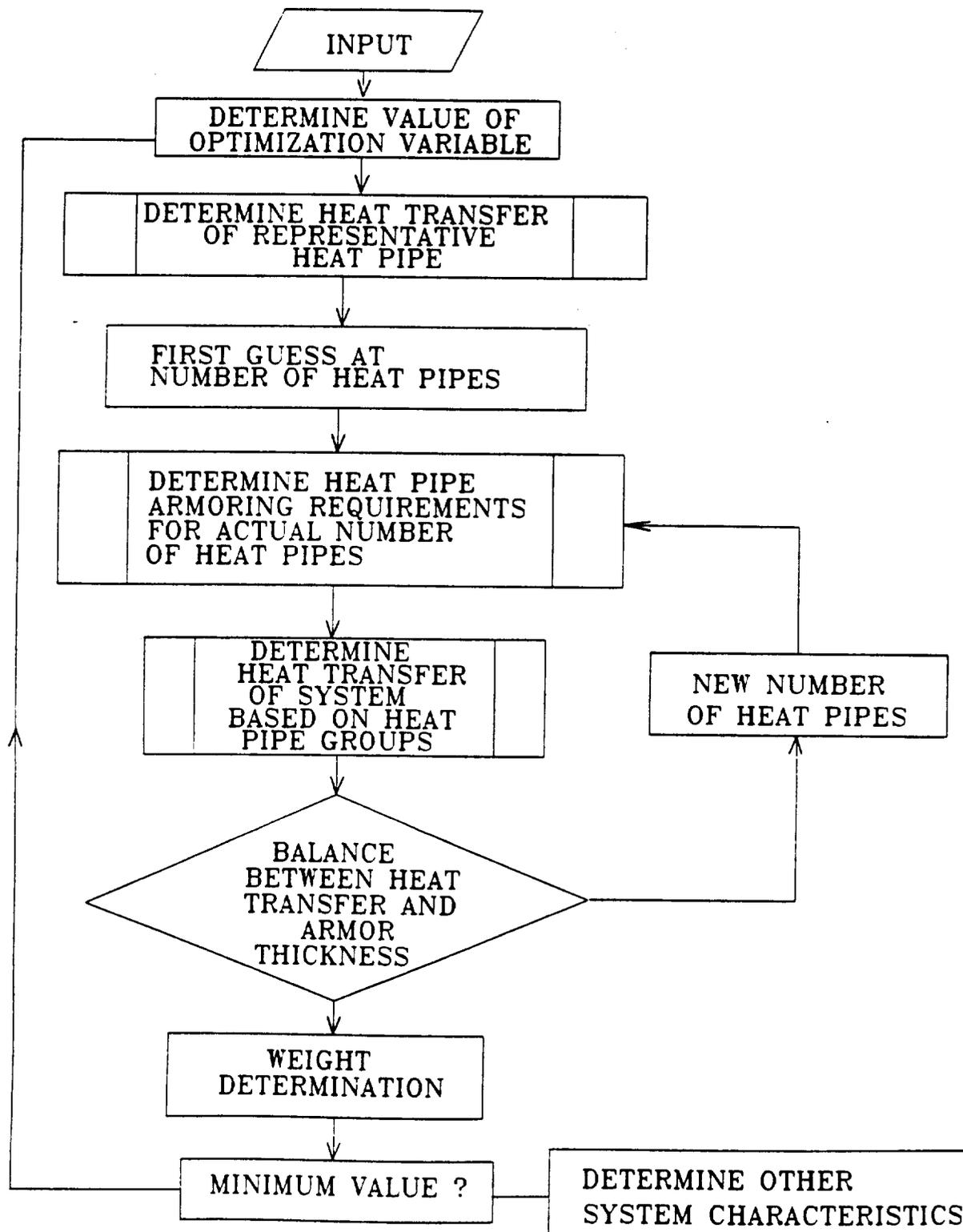


FIGURE 4: OPTIMIZED FLOW CHART



heat pipe can dissipate is determined. This calculation is done assuming the heat pipe has no protective armor. The value calculated is used to estimate the total number of heat pipes required for the entire radiator section. If the temperature and temperature change required in the radiator design requires more than one type of heat pipe working fluid, then the switch-off point (location where a different heat pipe fluid is used) is determined. This allows the determination of the required heat transfer of each group of heat pipes in a radiator section. The same procedure as outlined above is used for determining an initial guess for the required number of each heat pipe type to meet the specifications in the radiator section.

Once an initial guess for the number of all the heat pipe types is obtained, redundancy is included, and a total area is determined for the radiator section. This area is used along with the requirements on mission life, system altitude, redundancy, and required probability of radiator survival to determine the armor thickness for the heat pipes. At this point, a suitable estimate exists about the radiator section to begin the detailed analysis. A new value for the number of heat pipes is determined accounting for the armor thickness. At this time, an estimate of the required size of the transport duct is determined based on the number of heat pipes required. With this information, an estimate is made of the required armor thickness on the transport duct. This is based on the user specified transport duct design (i.e. location of the heat pipes in relation to the transport duct), duct material specifications, redundancy, and required survivability. When the armor thickness is determined, it is used to calculate a thermal resistance. With this known, an estimate of the transport duct heat transfer is calculated based on the average duct fluid temperature in the radiator section. This value is used to adjust the number of heat pipes required in the system. The iteration process with the heat pipes starts again and continues until the final design is converged upon for total number of heat pipes and transport duct size.

#### 2.1.4.2 OPTIMIZED APPROACH

The basic approach used for the analysis with the optimizing approach is not significantly different than that described above for the basic analysis. Several differences do exist though.

To be able to do the calculations for the radiator design numerous times for the mass minimization, groups of heat pipes are used instead of single ones to determine heat transfer capabilities. The total temperature drop of the radiator pumped loop fluid is broken into increments of approximately 5 K. Allowances are made when switch-off points between different heat working fluids are used. The required heat transfer of the fluid within this increment (i.e. product of mass flow, specific heat, and temperature change of the fluid) is determined. The arithmetic average temperature of the fluid within one of these increments is used as the temperature at the outside of the heat pipe evaporator. The heat transfer capabilities of a single heat pipe at that average temperature is calculated. The total number of heat pipes for the increment is determined by multiplying the ratio of total required heat transfer in the increment to that obtained for a single heat

pipe. This process continues for the entire radiator temperature drop and all heat pipe fluids. The mass of this radiator design is then calculated in the same way as is done for the non-optimizing approach.

The optimized design approach requires the user to choose upper and lower limits for the variable that is changed during the mass minimizing process (e.g. a minimum and maximum redundancy value must be specified when this is chosen as the optimizing variable). The system mass is initially determined for the specified upper and lower values as well as for the mid-point optimizing variable value. Brent's optimizing method determines the final variable value to give a minimized system design. This method uses the slope of system mass lines to determine the next variable guess for minimizing the system mass (see Reference 17 for additional information on this numerical method).

The technique used for minimizing the radiator system mass only allows one variable to be varied at a time. Therefore, when more than one heat pipe working fluid is required, the optimizing variable of only one heat pipe type is used to determine a minimum mass system. When this calculation is completed, the variable relating to the next heat pipe type is optimized to calculate the new system mass. This continues until all the different heat pipes types have been optimized for the specified variable and the final result reflects the overall system minimum mass.

It is not desirable to have the optimizing algorithm terminated due to a self imposed error in the program (refer to section 4.3), therefore, certain flags and conditions are set internal to the program during the analysis. Any situation which produces an error condition during the normal analysis will trigger a flag in the optimization run that establishes a high, artificial value of the system mass for that design point. The variable causing the error condition is eliminated from the analysis. This continues until a optimizing variable range is established that is with the program geometrical constraints. Therefore, even though the user may specify the optimized radiator to be established within a wide range of variable values, the program may reduce this range to one that can be addressed by the limitations of the code. In the output, the user is able to follow the events of the program to tell what has happened during calculations with out-of-bounds conditions. This method has worked a majority of the time, however, several instances have been found in which the optimization has not progressed correctly using this procedure. Therefore, it is recommended that when an error condition is triggered (indicated by an estimated mass of the system of 1E8 kilograms in the output), the user should rerun the analysis with a smaller specified range for the optimization variable.

## 2.2 GEOMETRY POSSIBILITIES

The radiator configuration can be varied substantially. The only basic constraint is that the design is one in which a fluid is transported to the evaporative sections of heat pipes. Various geometries can be designed via the use of the two view factors prescribed for the radiator system. Anything from flat plates, to cylinders, to cones, to a spoked wheel design, as well as

others, can be modeled with the use of independent view factors for two sides of the radiator. A user must spend some preliminary design effort to determine the correct values for the two view factors.

Within any geometry, the actual radiator operation can be accomplished in many ways. As mentioned previously, redundancy can be used for both the heat pipes and the transport ducts. Therefore, any number of independent transport ducts can be specified in a design, with any number of these being required to survive the entire mission. Attached to these ducts are the heat pipes that can also be redundant. These redundant heat pipes will simply increase the basic size of the transport.

The value of the heat pipe redundancy is expressed as a percentage of the number of heat pipes required for successful system operation at the end of mission. For instance, if it is determined that 100 heat pipes are required to reject the heat in a radiator section, and 8% redundancy is specified, there will actually be 108 heat pipes present in the final design. Due to the random nature involved in a failure from particle impacts, redundancy is used for all the heat pipes with different working fluids. Therefore, the same relative amount of extra heat pipes will be present for all the different working fluids.

#### 2.2.1            TRANSPORT DUCT

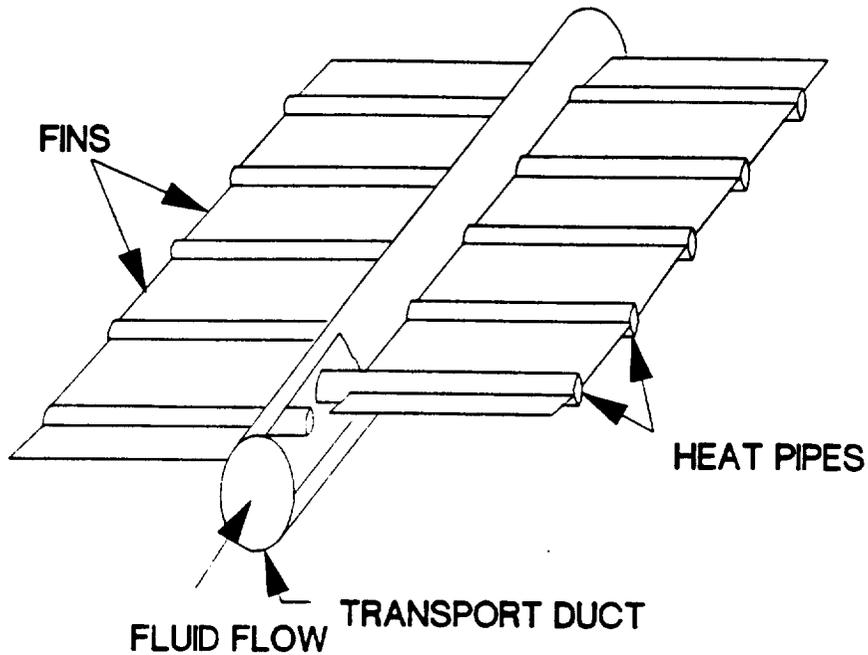
The transport duct carries the fluid heated by the heat source to the evaporative section of the heat pipes. The analysis done in the program does not assume any specific configuration of the transport duct or its interface with the heat source. The user information about the transport duct treats it as an arbitrarily shaped channel with a specified hydraulic diameter and wetted perimeter. Figure 5 shows the possible locations of the heat pipes relative to the transport duct. The heat pipes may simply be attached to the top of the duct or may actually penetrate the duct wall. In the former case, the heat pipes are conductively coupled to the transport duct fluid while in the latter situation the pipes are coupled by forced convection to the duct fluid. Additional permutations exist for the transport duct/heat pipe interface. The heat pipes may be attached to the transport duct on one or two sides. Refer to Figure 6 for an example of these two cases.

The final possibility dealing with the transport duct geometry is the allowance of a return duct in the system (refer to Figure 7). This situation may allow a better representation of an actual radiator geometry required in a system. The return duct may or may not have the same shape and size as the primary transport duct. Its specifications are entered independently into the code.

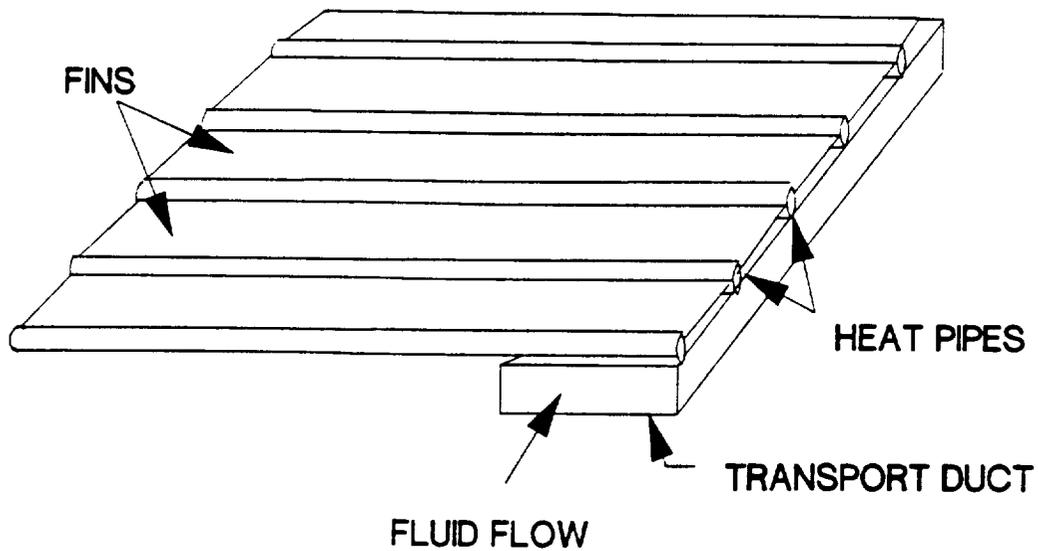
#### 2.2.2            HEAT PIPES

The heat pipe calculations and the geometries of both wick and envelope are extracted from the Lewis Heat Pipe Code. This allows for a multitude of possibilities in the heat pipe design. The choices of wick design include the

# FIGURE 5: HEAT PIPE/TRANSPORT DUCT CONFIGURATIONS

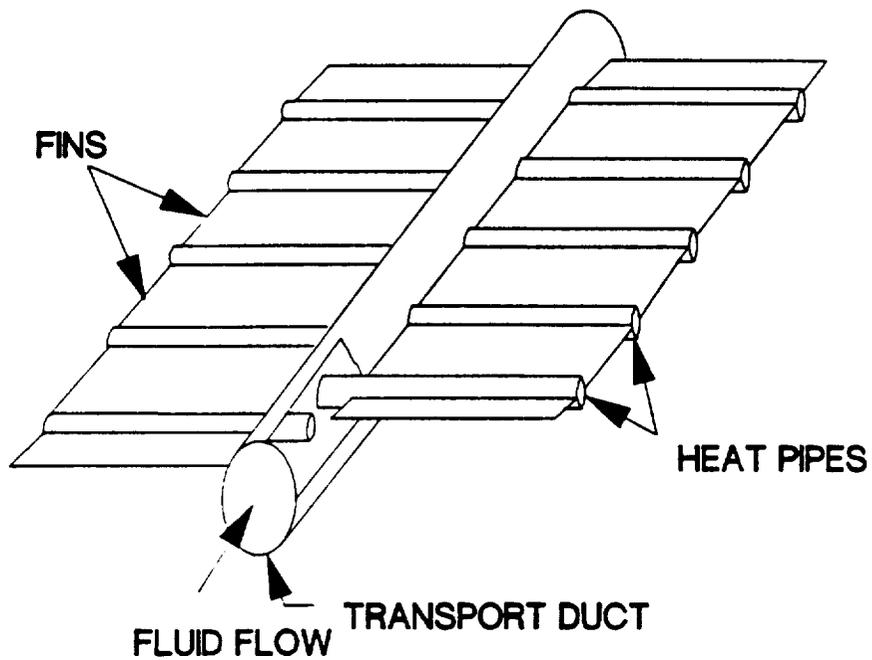


(A) HEAT PIPES PROTRUDE INTO DUCT

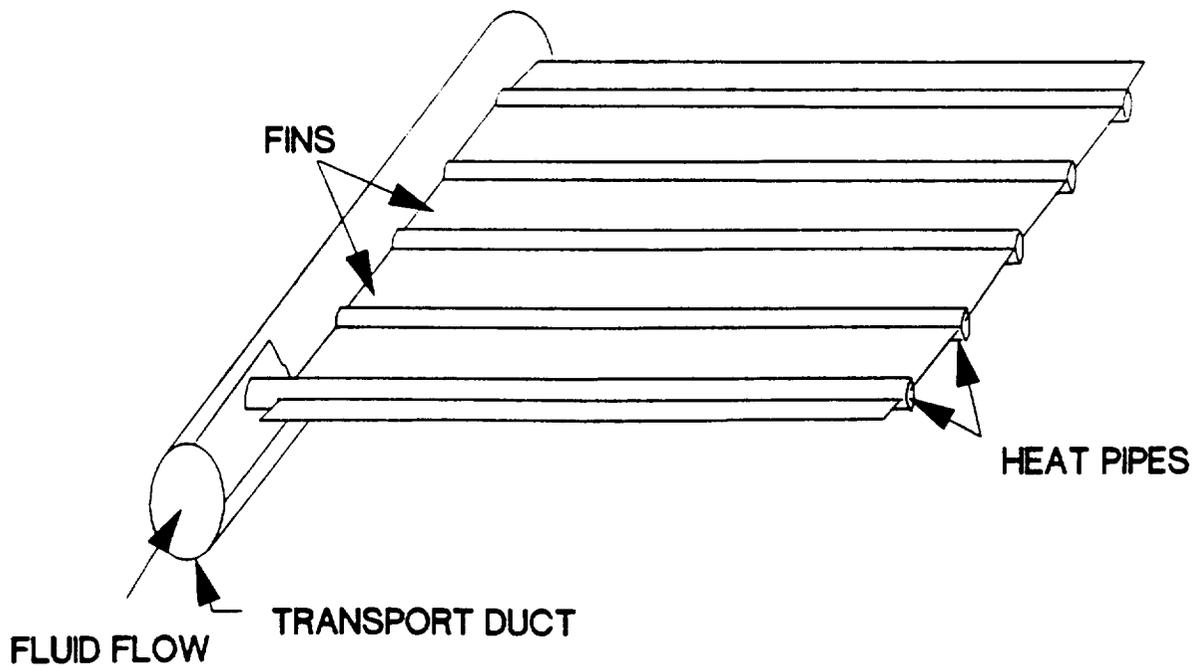


(B) HEAT PIPES ARE LOCATED "ON" DUCT

**FIGURE 6: HEAT PIPES ON ONE AND TWO SIDES OF TRANSPORT DUCT**

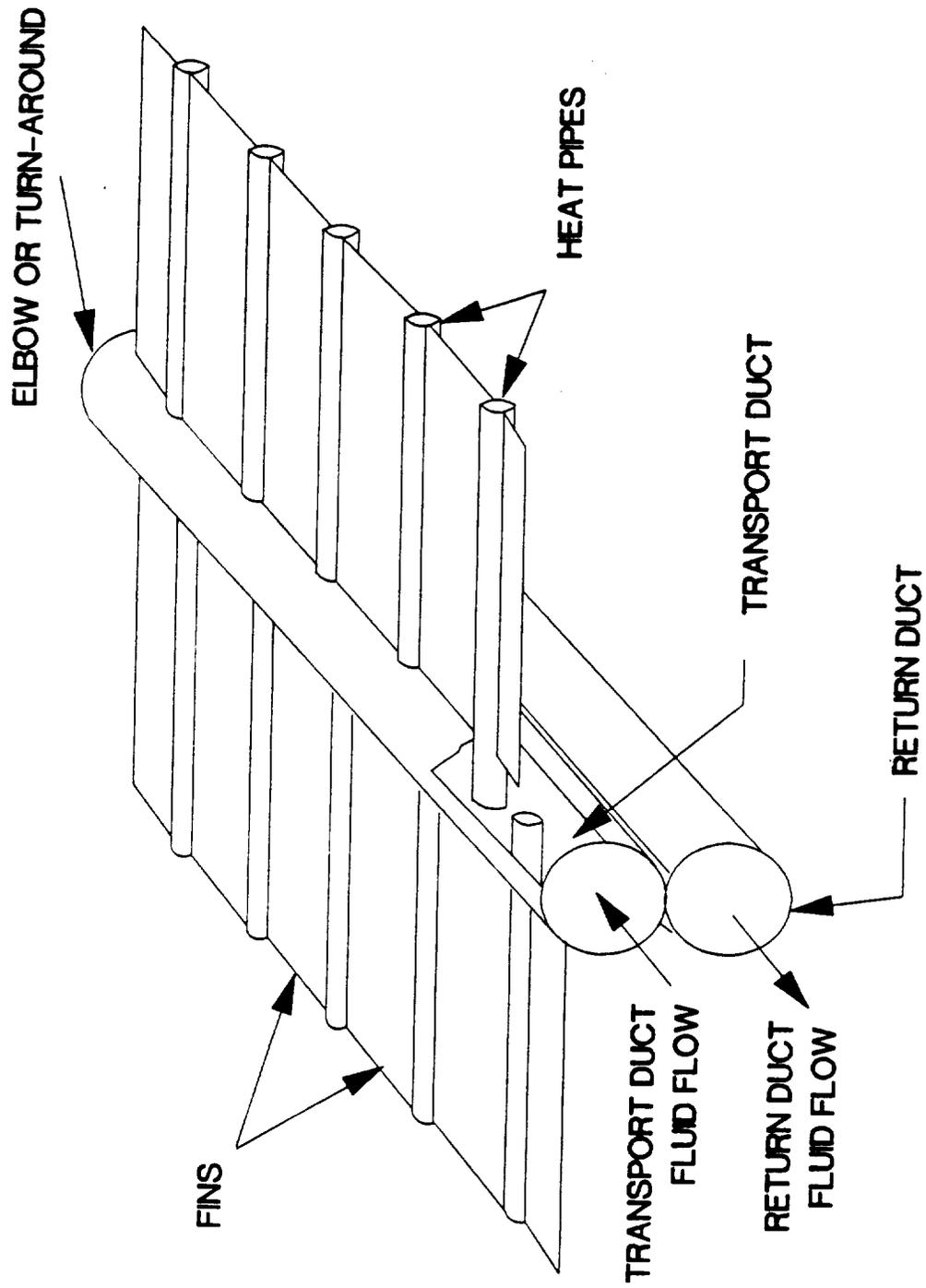


(A) TWO SIDES



(B) ONE SIDE

FIGURE 7: TRANSPORT DUCT DESIGN WITH RETURN DUCT



use of axial grooves, wire mesh screens, with or without arteries, sintered metal wicks, also with or without arteries, and a generic wick in which the user specifies all the geometric and hydrodynamic aspects of the wick structure. The basic assumed shape analyzed for the heat pipe envelope is a cylinder, however, specifying certain variables can result in the modeling of non-circular envelopes for the heat pipe cross section. The details of the requirements to describe non-circular heat pipes are described in Section 3.2. Also specified by the user are the heat pipe entrainment number, wetting angle of the fluid/envelope combination, and the nucleation radius available on the heat pipe envelope surface. These factors are also described in more detail in the user input sections of this manual.

## 2.3            MATERIALS

A built-in materials library is featured in the code. It is comprised of a substantial number of materials that have been considered for use in radiator systems. The choices available are described below with any applicable comments effecting their use.

### 2.3.1            FLUIDS

#### 2.3.1.1            TRANSPORT DUCT

The transport duct fluids available for use in the code are shown in Table 3. The code number for the fluid is used to identify it in the program input and output.

Table 3 : Transport Duct Fluids

<u>Fluid</u>	<u>Code Number</u>
Lithium	1
NaK	2
Helium	3
Toluene	4
Sodium	5
Potassium	6
Cesium	7
Water	8
Mercury	9
Methanol	10
Freon-11	11
Heptane	12
Dowtherm A	13
Ammonia	14
User specified properties	15

When the user input option is chosen, the program requires thermodynamic

information of the fluid that is to be used in the calculations. The information needed is specific heat, density, thermal conductivity, and viscosity. Temperature dependent properties are not available for use. Therefore, if a user specified fluid is to operate over a large temperature range, and its properties vary considerably over this range, the results obtained for the analysis may not be as accurate as desired. This must be kept in mind during a design. The program is easily expanded to include more working fluids, which is planned, however, those listed above constitute the current limits of the program.

2.3.1.2

HEAT PIPE

Available heat pipe duct fluids are shown in Table 4. Included in the fluid list are the associated numbers that identify the fluid in the input and output of the program as well as the suggested applicable temperature ranges (taken from Reference 10). It should be noted that no user properties can be entered for heat pipes. This is because the properties have to be entered as temperature dependent values due to the way in which the heat pipe performance is calculated. As with the transport duct fluid, the basic program can be modified to add additional fluids as information becomes available.

Table 4 : Heat Pipe Fluids

<u>Fluid</u>	<u>Code Number</u>	<u>Applicable Temperature Range</u>
Potassium	1	773 K to 1273 K
Lithium	2	1273 K to 2073 K
Sodium	3	873 K to 1473 K
Cesium	4	723 K to 1173 K
Water	5	303 K to 473 K
Mercury	6	523 K to 923 K
Methanol	7	283 K to 403 K
Freon-11	8	233 K to 393 K
Heptane	9	273 K to 423 K
Dowtherm A	10	423 K to 668 K
Ammonia	11	213 K to 373 K

2.3.2

METALS

2.3.2.1

LINERS/ARMORS/FINS/WICKS

The metals currently available for use in the code for liners (the use of liners for heat pipes and transport ducts is discussed in Section 2.3.2.4), armoring material, and fins are shown in Table 5. The associated reference number that is used to identify them in the program output and input is also shown. All of these materials may be used for the transport duct, heat pipes including the wicks, or fins. Any of them may be used as a liner or armoring

material in the system design, however, it should be noted that the metals with an asterisk do not have known armor property capabilities. Their impact coefficient will be determined by the following equation:

$$K_1 = 0.92/(\rho/1000.)^{0.5} \quad \text{with } \rho = \text{density in kg/m}^3$$

$K_1$  is the impact coefficient for the NASA Thin Model - refer to section 2.5.2 of this manual for detailed discussion of the mathematics of the calculations for impacts.

This equation is a curve fit of impact coefficients for materials with known armoring capabilities. It is assumed to be applicable to other ductile materials, however, the use of the materials with unknown armoring properties should be carefully scrutinized when used in a radiator design.

Table 5 : Materials for Liners, Armor, Fins, and Wicks

<u>Metal</u>	<u>Code Number</u>
Stainless steel	1
Titanium	2
Beryllium	3
Aluminum	4
Magnesium lithium	5
Niobium-1 zirconium	6
User properties	7
Iron**	8
Nickel**	9
Copper**	10
Tungsten**	11
Inconel**	12
Molybdenum**	13
Tantalum**	14

\*\* Indicates that armoring property capabilities are currently unknown, and their impact coefficients are determined by the above equation. This aspect of the analysis has not yet been changed in the program, and currently, the use of these materials do not provide any armoring protection.

The user specified properties option allows the incorporation of any material for use in the program. This, therefore, allows the incorporation of such things as composite materials for use in a radiator design. The properties required for system design include density and thermal conductivity. The armoring capabilities of a user defined material is calculated in the same manner as that for the materials with unknown protection capabilities. As with the user defined fluid properties, a temperature dependence of the user defined materials is planned, but not

currently available. Therefore, the same warning exists for materials that have very temperature dependent properties used in a system that experiences a large temperature change.

#### 2.3.2.2                    BUMPERS

As of yet, no calculations are included in the code to allow for use of offset bumpers in the determination of armoring requirements. Input exists in the program for the use of bumpers, but the information is not used. Only basic armoring calculations are assumed to occur.

#### 2.3.2.3                    COMPATIBILITY INFORMATION

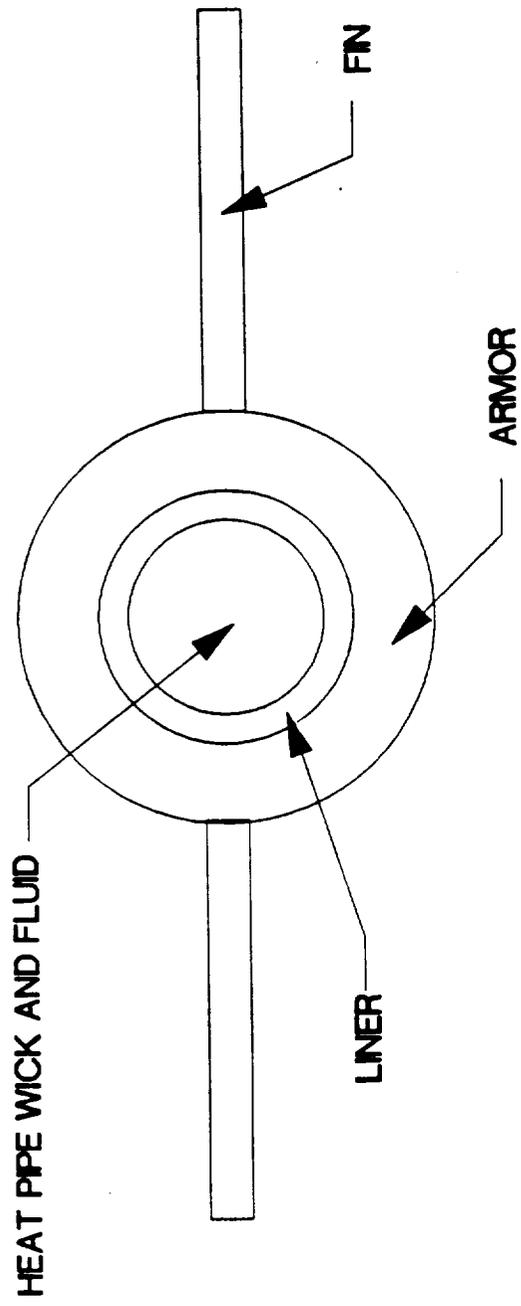
Much experimental work has been done with heat pipes, and it has been determined that not all heat pipe working fluids and heat pipe envelope materials are compatible with one another. Two materials may produce an interaction that causes the heat pipe to fail. A listing of known compatibilities (acceptable and adverse) is contained in Reference 11. This information has been included in the HEPSPARC code. Based on the material choices, information is provided in the code output to indicate known compatibility information between the heat pipe fluid and its wick and envelope material. Even though the transport duct and transport fluid do not behave in the same manner as the heat pipe, compatibility information is also provided for the duct system to alert the designer of any known history regarding the materials chosen for the overall design.

#### 2.3.2.4                    LINERS

A material is chosen for a heat pipe or transport duct system to provide maximum armoring capabilities. However, often this material is not compatible with the fluid it must contain. In such a case, a liner may be employed in the system (refer to Figure 8). This provides a material barrier between the fluid and outside material. It allows the use of the best armoring materials with the best heat pipe fluids even though they may be incompatible. The liner material will also offer some armoring capabilities.

This code allows for the design of transport duct system and heat pipes with the liner material. Even though the user may specify a particular combination of armor, liner, and fluid, it still may not be manufacturable. Nothing is contained in the code to estimate the compatibility between the armor and liner material. Several things are recommended to the designer to evaluate this aspect. One is to examine the coefficients of thermal expansion of the two materials and the stress that would be induced in them for the radiator design. If one of the materials will yield, the use of the material combination may be questionable. An additional area to check is the possibility of a chemical interaction between the liner and armor material.

FIGURE 8: ARMOR/LINER LOCATION



### 2.3.2.5      PROPERTIES

The material properties used for the analysis in this program can be obtained from a source listing of the code (refer to section 6.0 of this manual). The data was taken from a combination of places. Much of the material information was taken directly from the NASA Lewis Heat Pipe Code (Reference 9). Additional data was the result of material property curve fits obtained from various literature sources (Reference 12). The impact data was obtained from a NASA report on the subject (Reference 8).

## 2.4            HEAT TRANSFER DETAILS

### 2.4.1            OVERVIEW

This section of the manual discusses in detail the methods employed to determine the heat transfer that occurs from the radiator system. It is meant to provide sufficient information and references to allow the interested user to follow the program calculations and structure.

The basic method employed for the code has already been described. The program heat transfer calculations operate in the same manner for both the optimization and non-optimized version of the code. The thermal resistance of various sections of the design are determined and the temperature drop through these resistances is calculated along with the heat transfer from the particular section of interest. The heat transfer calculated is equated to the temperature drop experienced by the transport duct fluid. At this point, the next heat pipe, sections of heat pipes or transport ducts are addressed in the calculations. The code progresses through the radiator system until the overall design requirements have been met (i.e. the transport duct fluid has met its specified temperature change). This entire process includes the armoring methodology described elsewhere in this manual.

### 2.4.2            TRANSPORT DUCT FLUID

#### 2.4.2.1            BASIC EQUATIONS

The heat transfer coefficient to determine the temperature drop from the transport duct fluid to either a heat pipe immersed in the fluid or to the duct wall itself is determined by standard empirical relationships. The different areas and fluids in the transport duct require several different correlations for the total range of applicability of the program. The equations used in the program are described below.

Flow across a heat pipe evaporator: Heat transfer from fluid to a cylinder;

Liquid metals:

$$\bar{h} = (k/D_{\text{outside of heat pipe}})[5.0 + 0.025(\text{Re}_D \text{Pr})^{0.8}]$$

Other fluids:

$$\bar{h} = (k/D_{\text{outside of heat pipe}})(0.26\text{Re}_D^{0.6}\text{Pr}^{1/3})$$

where  $\text{Re}_D$  = Reynolds number based on heat pipe evaporator diameter

$\text{Pr}$  = Prandtl number

Heat transfer from fluid to transport duct:

Liquid metals:

$$\bar{h} = (k/D_{\text{outside of heat pipe}})[6.133 + 0.015(\text{Re}_D\text{Pr})^{0.8}]$$

Other fluids:

Laminar flow:

$$\bar{h} = 3.66(k/D_{\text{outside of heat pipe}})$$

Turbulent flow:

$$\bar{h} = (k/D_{\text{outside of heat pipe}})(0.023\text{Re}_D^{0.8}\text{Pr}^{0.3})$$

here,  $\text{Re}_D$  is based on the transport duct hydraulic diameter

When a condensing fluid is stipulated, a constant heat transfer coefficient of  $15,000 \text{ W/m}^2\text{K}$  is used. This is done due to the uncertainty involved with the heat transfer coefficients for two-phase fluids in a zero gravity environment. This value is typical of condensing coefficients present on Earth. It can be easily modified when an acceptable correlation is found for zero gravity situations.

#### 2.4.2.2

#### AREA MULTIPLIER

A multiplier may be used for the evaporator area of the heat pipe. This option may be exercised when the thermal resistance between the transport duct fluid and a heat pipe in the fluid stream is high. This variable is used as a simple multiplicative factor of the existing evaporator heat transfer area. It increases the area of heat transfer in order to reduce temperature drops that may occur. The use of this variable allows the design of heat pipes that have convective fins attached to the evaporator section that increase heat transfer. This variable allows the use of such fins without knowing the details of the fin geometry. Specifically, this variable is applicable for a Brayton system in which the working fluid is a gas that may have a low convective heat transfer coefficient. Therefore, to reduce the temperature drop of the system, the evaporator area would be increased. A value of 1.0

for this variable will allow an analysis to proceed with the basic heat envelope determining the heat transfer area.

#### 2.4.3

#### HEAT PIPE

In situations in which more than one heat pipe fluid is required for a system, the switch-over point between fluids is governed by the recommended upper bounds of the lower operating temperature heat pipe fluid. This allows a radiator to be designed for an end of life operating condition in which specified final system requirements are stipulated. Such a configuration exists when all redundant heat pipes have been destroyed, and the radiator is just able to meet the system heat transfer requirements. In the transport duct, non-operational (redundant) heat pipes exist upstream heat pipe fluid switch-over points. At these points, the lower temperature heat pipe fluid will have to operate at its maximum temperature. Therefore, by specifying the a switch from a higher temperature heat pipe fluid to a lower one to occur at as high a temperature as possible, end of mission requirements will be able to be met without much possibility of the heat pipes operating beyond one of their thermal or hydraulic limits. Before the radiator reaches this end of mission configuration, the transport duct fluid at the switch-over points will be at a lower temperature and will require the heat pipe will simply operate further into its recommended intended design range.

#### 2.4.3.1

#### EVAPORATOR/CONDENSER

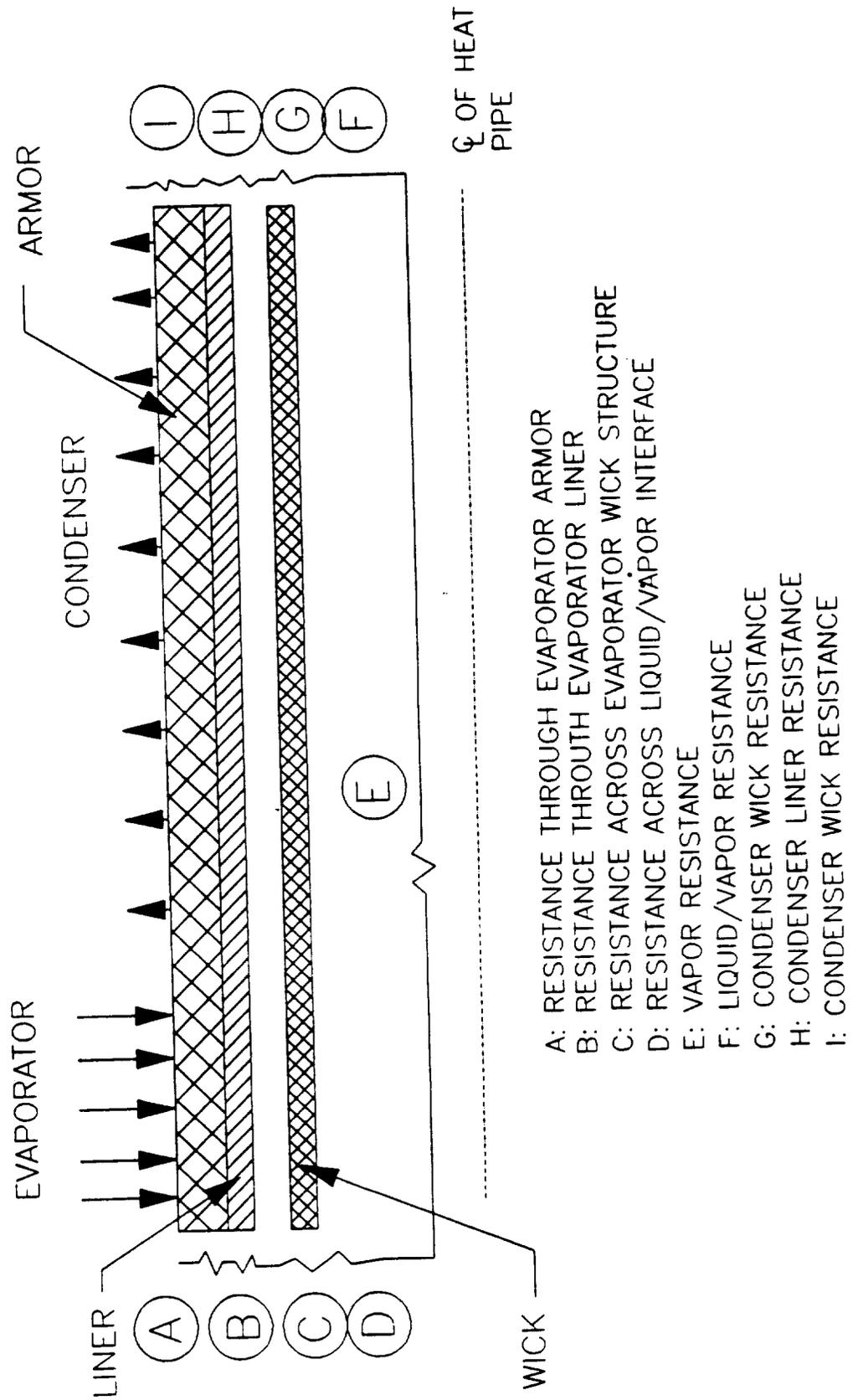
The heat pipe heat transfer is calculated in the same manner as is done in the NASA Lewis Heat Pipe Code (Reference 9) and therefore, the specific equations will not be furnished here. It is done via the use of a heat transfer resistive network that accounts for all sections of the heat pipe. The heat pipe model uses three separate nodes; one in the evaporative section and the remaining two in the condenser. The network contains all the elements that exist to retard heat transfer from the outside of the evaporator wall to the outside of the condenser wall (see Figure 9). The resistances that are taken into account during the analysis of the heat pipe are the resistance through the outside armor and liner wall in the evaporator, the wick thermal resistance, the resistance across the liquid vapor interface in the evaporator, and the resistance through the vapor itself down to the condenser section of the heat pipe. In the condenser the resistance network is just reversed from that in the evaporator, i.e. across the vapor/liquid interface, through the condenser wick structure, and then through the liner and armor in the condenser. The resistances for the condenser section is done at two separate nodes to account for the possibility of a large temperature drop through the heat pipe at near thermal-hydraulic limit conditions.

#### 2.4.4

#### FINS

The heat transfer from the radiator occurs due to radiation interchange from the outside surfaces to the space environment. The heat pipes are assumed to have conducting fins located between adjacent pipes. These are

FIGURE 9: HEAT PIPE THERMAL RESISTANCE NETWORK



used in radiator design to help reduce the mass of the system. The fins decrease in temperature along their length due to the heat loss from their surface. Typically, the effectiveness of the fin is expressed as a fin efficiency. This is the ratio of amount of heat a fin actually transfers to the amount of heat that could be transferred from a same sized isothermal surface at the temperature of the fin base. Due to the fin/heat pipe configuration, not all of the heat radiated from the surface will be directed towards the space sink (see Figure 10). Some of the energy that emanates from the heat pipe will be intercepted by the fin or adjacent heat pipes, and thereby reducing the effectiveness of the heat pipe surface. The fin will also radiate energy that is intercepted by the heat pipes. This phenomenon is accounted for in the code. An analysis was done to determine the effects of geometry on the fin and surface efficiencies. The description and results of that analysis are presented below.

#### 2.4.4.1                    GRAY BODY ANALYSIS

The procedure for determination of surface and fin efficiencies is outlined in Reference 13 and was performed on the basic configuration shown in Figure 10. The surfaces were assumed to be gray, i.e. they were not assumed to be perfect emitters and absorbers. The analysis broke the configuration down into differential sized elements. View factors were determined between all elements, and an iterative scheme was developed to determine the radiosities of the differential elements. From that, the total heat transferred from the surfaces was determined. This analysis was done for various combinations of fin length, thickness, pipe size, and surface emissivities. Additionally, the analysis allowed adjacent heat pipes to be operating at slightly different temperatures which may actually be the case in a radiator. The heat transfer values calculated were then compared to a gray, flat, isothermal surface of the same size to establish the effectiveness of the heat pipe, via a surface efficiency, and the fin, via a fin efficiency. These values are used in the code in a manner described in the following section.

#### 2.4.4.2                    TABULATED DATA

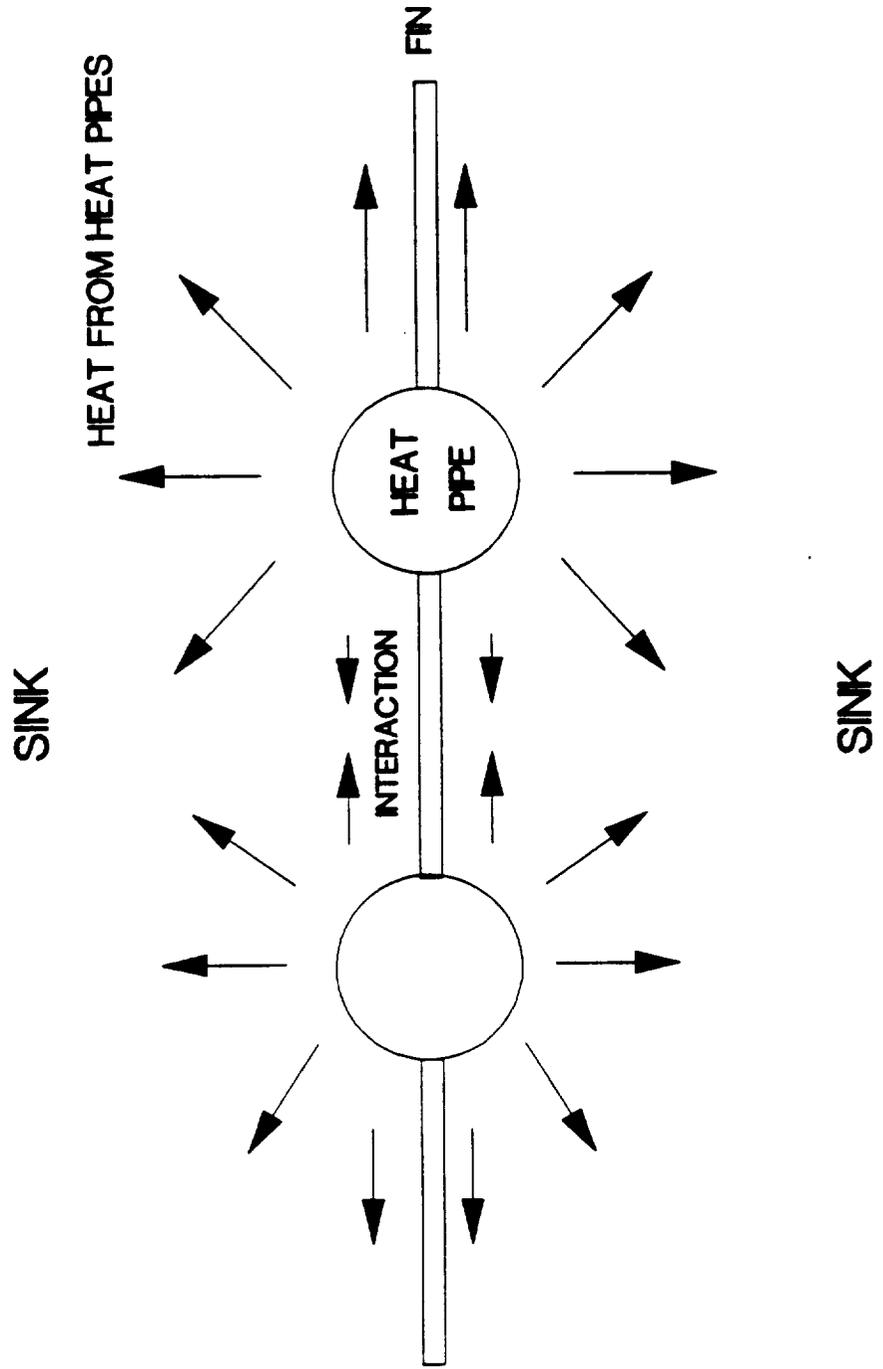
The results of the gray body analysis has been entered into HEPSPARC by means of a simple look-up table. Geometrical factors, temperatures, thermal conductivity, and surface emissivity values are all used to determine the appropriate table location in which to obtain surface and fin efficiencies. A factor to account for the effect of non-isothermal adjacent heat pipes is also in tabulated form, and is used as a multiplicative adjustment to the efficiency values.

The total heat transfer that occurs from the outside of the heat pipe surface is calculated from the data obtained in the table as:

$$Q = \frac{1}{2}(F_1+F_2)\sigma(T_{\text{surface}}^4 - T_{\text{sink}}^4)(\eta_{\text{surface}}A_{\text{heat pipe}} + \eta_{\text{fin}}A_{\text{fin}})$$

with  $F_1$  or  $2 =$  view factor of side 1 or 2 of the radiator to

FIGURE 10: HEAT PIPE/HEAT PIPE/FIN BASIC ARRANGEMENT



$T_{\text{sink}}$

$\sigma$  = Stefan-Boltzman constant

$T_{\text{surface}}, T_{\text{sink}}$  = heat pipe and sink temperatures

$\eta_{\text{surface}}, \eta_{\text{fin}}$  = adjusted surface and fin efficiencies respectively. These already account for non-isothermal adjacent heat pipes and a specified emissivity to be present on the surfaces. That is why  $\epsilon$  does not appear in the above equation.

$A_{\text{heat pipe}}, A_{\text{fin}}$  = Total heat pipe and fin surface areas respectively

One desired modification to the program will be to allow different emissivities on the fins and heat pipes. Current restrictions allow only one emissivity to be specified for all of the radiator surfaces. This does not necessarily represent a condition that would actually exist when radiator design uses different fin and base materials.

## 2.5            ARMOR DETAILS

The methodology employed for the determination of armor thickness of the radiator surface, specifically the heat pipes and transport ducts, is described in this section.

### 2.5.1            FLOW CHART

The basic flow chart of the calculation of the armor thickness is shown in Figure 11. The details involved in the process, including all the supporting equations are presented below. The process requires an iterative method of solution to determine the armor thickness of the radiator.

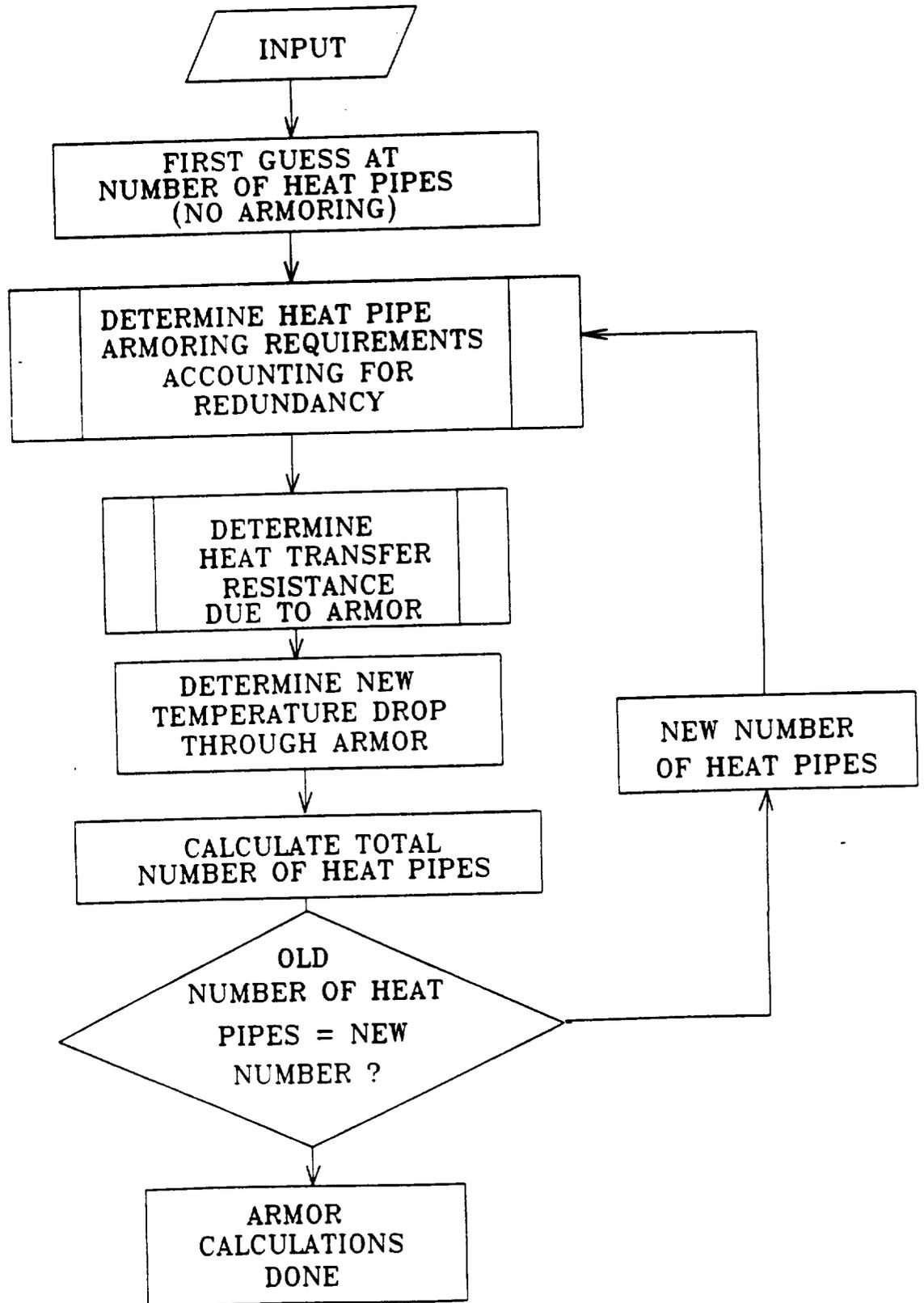
### 2.5.2            BASIC ARMORING EQUATIONS AND METHODS

The method followed for a determination of the armor requirement is taken directly from Reference 6 and is simply synopsized here for completeness of this document. Several modifications were made to the basic approach outlined by Fraas to tailor the calculations to the situations being analyzed. They will be pointed out as required. If the reader is unfamiliar with basic armoring methodology, it is recommended that Reference 6 be reviewed prior to trying to understand this section.

Micro-meteoroids:

Particle distribution models exist that describe the level of certain

FIGURE 11: DETAILED ARMORING CALCULATION



mass particles present in the space environment. For micro-meteoroids, the near earth flux has been modeled as:

$$\log_{10} N_t = -14.37 - 1.21 \log_{10} m$$

with  $N_t$  = average meteoroid flux (number of particles, of mass equal to or greater than  $m$  grams, per  $m^2$ -s)

This expression can be corrected for the defocusing effects of the earth's gravitational field by multiplying by:

$$G_e = 0.568 + 0.432/R \quad (R = (6378+H)/6378 \quad H = \text{orbital altitude in km})$$

and

$$E = (1 + \cos\theta)/2 \quad \text{with } \theta = \arcsin[6378/(6378 + H)]$$

The thickness of a given material for incipient penetration by an impacting particle has been estimated as:

$$t = K_1 m_p^{0.35} \rho_p^{0.17} V^{0.88}$$

where

- $t$  = material thickness, cm
- $K_1$  = penetration constant of given material
- $m_p$  = mass of particle, g
- $\rho_p$  = density of particle, g/cm<sup>3</sup>
- $V$  = particle velocity, km/s

This is the NASA thin Plate model. The equation can be solved to determine the mass of a particle required to penetrate a given material thickness. This is substituted into the flux equation to determine the flux of particles ( $N_{ti}$ ) having mass equal to or greater than the mass required to penetrate the material thickness for the given velocity ( $V_i$ ). Combining all the above yields:

$$N_{ti} = 4.27 \times 10^{-15} G_e E t^{-3.45} K_1^{3.45} \rho_p^{0.58} V_i^{0.31}$$

This flux corresponds to a particular velocity increment. In order to obtain the total value of the flux, the particle velocity profile is broken apart and the probability of each velocity is then used to determine an overall lethal flux value ( $N_{1t}$ ).

$$N_{1t} = \sum N_{ti} P_i \quad \text{where } P_i = \text{probability of velocity } V_i \text{ occurring for the micro-meteoroids}$$

When this is done for the micro-meteoroid distribution, the following expression results:

$$N_{1t} = 7.15 \times 10^{-11} G_e E t^{-3.45} K_1^{3.45} \rho_p^{0.58}$$

The particle density,  $\rho_p$ , is assumed to be 0.5 g/cm<sup>3</sup>.

The probability of impact of an exposed radiator area by n or fewer lethal particles during a mission is described by a Poisson distribution:

$$P_{(h \leq n)} = \exp(-N_{1t}AT) \sum_{r=0}^{r=n} (N_{1t}AT)^r / r!$$

where

- $P_{(h \leq n)}$  = probability of impact by n or fewer lethal particles. This corresponds to the probability of survival of the radiator heat pipes or transport duct systems.
- $N_{1t}$  = lethal particle flux, particles/m<sup>2</sup>-s
- A = exposed radiator area to be protected, m<sup>2</sup>
- T = mission duration, seconds

An iterative technique is used to determine the values in the above equation. The required area is determined from the heat transfer calculations (in the heat pipe case), or from the assumed design (for the transport ducts). The redundancy of the system is used to increase this area. The number of redundant components represents the value of n in the above equations. For a given thickness, redundancy, altitude, and material, the probability of n number of lethal impacts is determined. This probability is then compared to the desired system probability of survival. The thickness is adjusted and the calculation repeated until the correct probability is determined. The thickness calculated is used to redetermine the system heat transfer.

Debris:

Space debris is addressed in the same way as the micro-meteoroids. The total lethal flux for debris is determined to be:

$$N_{1t} = 8.89 \times 10^{-10} t^{-2.22} K_1^{2.22} \rho_d^{0.37}$$

In this case, the debris density,  $\rho_d$ , is assumed to be that of aluminum, or 2.7 g/cm<sup>3</sup>. Also note that there is no correction for earth defocusing or system altitude. This level of flux is taken as the value estimated to be present for year 2020.

If the radiator exposed areas were the same for the micro-meteoroids and debris, the two fluxes calculated above would simply be added to give a grand total flux for use in the Poisson expression and in the determination of the material thickness iteration scheme. However, different areas may exist for the use with the two fluxes. The areas used, and their justification is described in Section 2.5.5.

Space debris and micro-meteoroid fluxes have a definite directional nature to them that may be calculated. Specific orbital information related to the spacecraft is required. However, this program is not capable of such specific analysis, and the directional aspects are not included. The flux levels presented are for a worst case situation to produce a conservative

design.

### 2.5.3 BASIC BUMPERING METHODOLOGY

Bumpering refers to the use of armor that is not directly adjacent to the structure being protected. A certain distance exists between the bumper and underlying surface. The concept behind bumpering is that the use of the bumper will cause impacting particles to either be vaporized due to impact with the bumper or to be broken apart. The resulting fragments will be of a lower mass and be dispersed over the underlying surface. This surface may be thinner than if it were exposed to the normal distribution of particles since the particles reaching it have a lower mass, and therefore, a lower lethal particle flux.

The method used to determine the effectiveness of the bumper is given in Reference 8, however, as mentioned before, this is currently unavailable as part of the code calculations. This section was added to make the user of the code aware of the need and desire to include this armoring aspect in an improved version of the radiator code.

### 2.5.4 USE OF MULTI-LAYER MATERIALS

In designs in which more than one type of material is used for the armor surface (e.g. using a liner material on heat pipes), the relationship specified between lethal particle flux and thickness may be conservative. Therefore, an alternative calculational method has been established. Whereas the equations determined above were for the thickness of material at incipient penetration (NASA Thin Plate Model), when a multi-layer material is used, the required thickness may be reduced (Reference 14).

The analysis is based on the model of an impact of a particle with a semi-infinite body (NASA Thick Plate Model). The basic equation relating these is (Reference 6):

$$P_o = K_m m^{0.35} \rho_m^{0.17} v^{0.67}$$

where  $P_o$  = depth of penetration, cm  
 $K_m$  = material constant  
 $m$  = mass of micro-meteoroid, g/cm<sup>3</sup>.  
 $\rho_m$  = micro-meteoroid density. Use a value of 0.5 as before.  
 $V$  = impact velocity

A correction factor (CF) to this depth of penetration is then applied to determine the wall thickness when a multi-layer material is used for a thin walled structure.

$$t = CF \times P_o$$

The analysis proceeds as before to determine the lethal flux for the micro-meteoroid distribution. It is determined to be:

$$N_{1t} = 5.79 \times 10^{-12} G_e E t^{-3.45} C F^{3.45} K_a^{3.45} \rho_p^{0.58}$$

For this equation, the particle density,  $\rho_p$ , is again assumed to be 0.5 g/cm<sup>3</sup>.

The correction factor used may have any value. A value of 1.5 has been used previously in the SP-100 analysis (Reference 14), and therefore, it is the only choice currently available.

The same procedure used above may be followed for the space debris flux to give:

$$N_{1t} = 2.69 \times 10^{-10} t^{-2.22} C F^{2.22} K_a^{2.22} \rho_d^{0.37}$$

Again, the grand total of these two fluxes will be used in the Poisson distribution calculation from above. These are the equations used for lethal flux determination in the iteration calculations when a correction factor is specified.

The material thicknesses determined from all the above calculations (NASA Thin and Thick Plate models) are used to determine the actual required armor thickness to account for the presence of any liner on the section being analyzed. The thickness (t) of a liner is converted into an equivalent armor thickness by use of the following relationship:

$$t_{\text{equivalent armor}} = K_{1,\text{armor}} t_{\text{liner}} / K_{1,\text{liner}}$$

where the  $K_1$  values are the impact coefficients for the armor and liner materials for the NASA Thin Model

This equivalent thickness is subtracted from the calculated required thickness value to determine the actual armor thickness.

### 2.5.5 VULNERABLE AREAS

The area used in the determination of the exposed area for the armoring calculations may be varied somewhat. The flux of micro-meteoroids is considered to be isotropic in nature, and therefore, a lethal particle may arrive from any direction. Therefore, the total exposed area of the heat pipes and transport duct is required to be used for determining the armoring requirements for micro-meteoroids. In the case of a heat pipe, the exposed area is the circumferential area of the pipe.

The area to be used for space debris may be different. It is unknown whether debris behaves isotropically or in a more planar manner suggested by some (Reference 15). In the former case, the total area would have to be used, but in the latter, a projected area would constitute the exposed surface. In that case, the diameter of a heat pipe (multiplied by the exposed length) is used for the determination of armor for the space debris flux.

All the areas used are corrected for the configuration of the radiator design. The heat transfer view factor of the two "sides" of the radiator surface is used to reduce the exposed area. This is done to compensate for the fact that a radiator design may help shield itself. For instance, a cylindrically shaped radiator will obviously not have the same probability of impact on its interior surface as it does on its outside. Therefore, it is assumed that the same view factor exists to the debris and micro-meteoroid source that exists for the surfaces to the specified heat sink temperature. Additionally, for the transport duct, some additional shielding will occur if a return duct is added to the system. This shielding will reduce the exposed area of the duct. The amount of the shielding will be determined by the specific configuration of the duct design. Since it would be very difficult to attempt to determine all the data required to calculate the amount of shielding that occurs when a return duct is used in a system, it has been assumed that 75% of the total surface area of a round or non-round transport will be exposed to the space environment fluxes of debris and micro-meteoroids when a return duct is used and the total surface area is used for armor determination. When a projected area is assumed for use with the micro-meteoroids, only half of this value of vulnerable area (37.5%) is used for armor determination on the transport duct. These values were determined to be present on specific designs HEPSPARC was used with. It is believed to be a good estimate of the vulnerable area present when a return duct is used. If the user does not feel that it correctly models a particular design, it may easily be changed within the program.

## 2.6            OTHER DETAILS

This section details other features of the code. This includes pressure drops and other details of the transport duct fluid as well as details concerning stress levels calculated in the code.

### 2.6.1        PRESSURE DROP

The pressure drop experienced by the fluid in the transport duct is estimated in the program. This allows for the determination of pumping power (see below) so a designer may estimate this aspect of the radiator system. The pressure drop and pumping power will detract from the overall system performance and will have to be supplied by some system power source.

The pressure drop in the system is dependent on the frictional energy loss the fluid undergoes while moving through the transport duct. The code breaks the calculation down into several different sections for analysis. When the heat pipes do not project into the transport duct, the total pressure drop is determined by the basic duct flow equation:

$$\Delta P = 4\rho V^2 f L / (2D) \quad \text{where}$$

- V = fluid velocity
- f = friction factor (see below)
- L = length of duct
- D = hydraulic diameter of duct
- $\rho$  = density of fluid in transport duct

The equations used for friction factor vary in the above analysis with respect to the Reynolds number of the flow. They are determined as follows:

For Reynolds number (Re) < 5000

$$f = 16/Re$$

and for  $5000 \leq Re \leq 30,000$

$$f = 0.079Re^{-0.25}$$

and for  $Re \geq 30,000$

$$f = 0.046Re^{-0.20}$$

When the heat pipes project into the duct, the Reynolds number used is dependent upon the area being examined. Areas required to be examined include the entrance and exit of the radiator panels, the area in between heat pipes, and the area directly adjacent to the heat pipes. A Reynolds number is determined for each of these sections and the corresponding friction factor determined. Each of the pressure drops associated with these areas is determined and added to estimate the overall pressure drop expected in the entire system. The pressure drop for the total number of panels determines the value for each independent radiator loop.

The friction characteristics for the pressure drop determination were taken from Reference 16. Although the correlations are specifically for round pipes, the use of the hydraulic diameter should give reasonable estimates of the friction factor for the pressure drop calculations for non-round transport ducts.

The pressure drop due to heat pipes being in the duct is accounted for by determining the pressure drop over a single tube in cross-flow. It is realized that this is not the best way to model the situation due to possible effects from the proximity of the transport duct. Some type of single, in-line tube bank correlation may be better, but none was found for incorporation into the code. It is estimated that the use of the single tube in cross-flow will produce conservative results. Tube banks typically have a lower pressure drop due to a shielding effect from upstream tubes.

Loss coefficients can be added to the system pressure drop to account for the presence of elbows, restrictions, and other actual duct possibilities. The way in which they are used is to multiply the loss coefficients and the velocity head of the transport duct fluid to obtain the additional system pressure drop. No use of the equivalent diameter method is employed.

### 2.6.2      PUMP WORK

Pump work is estimated based on the calculated system pressure drop. It is the volume flow rate of fluid (Q) multiplied by the pressure drop:

Pump work =  $Q\Delta P = m\Delta P/\rho$  with  $m$  = mass flow rate of fluid in transport duct  
 $\rho$  = density of fluid in transport duct  
 $\Delta P$  = system pressure drop

This estimates the power required for a 100% efficient pump to move the fluid through the radiator system as designed. Actual requirements will depend on any additional pumping requirements present in the loop as well as the hydraulic and electrical efficiency of the pump and motor combination chosen for use.

### 2.6.3 STRESS ANALYSIS

The hoop stresses in heat pipes and transport ducts are estimated in the program. Even though the transport duct, and at times the heat pipes, may not be circular in shape, the stress determined in a cylinder is used to estimate the effect of pressure in the system.

Hoop stress:  $\sigma = Pr/t$  with  $P$  = pressure of fluid in transport duct or heat pipe  
 $r$  = radius of heat pipe (based on diameter of heat pipe used for armor determination) or hydraulic diameter of transport duct divided by 2  
 $t$  = thickness of wall of transport duct or heat pipe (includes liner and armor thickness)

### 3.0 USER INPUT

#### 3.1 INTRODUCTION

This section is used to provide a line by line description of the how the code is used. Both the interactive and non-interactive input characteristics will be explained.

The non-interactive method will be addressed initially. The procedure that will be followed will be to show the actual lines of data required for the program. The meaning of each variable will be explained as well as any applicable variables or flags that may be set or triggered within the program by a given response. This will help in the description of the interactive use of the program. All combinations of responses will be addressed for both the optimization and non-optimized use of the code. The questions as they appear from the code will appear in **bold faced text** as will the lines of data that are created in the input file.

#### 3.2 INTERACTIVE AND NON-INTERACTIVE METHODS

##### 3.2.1 NON-INTERACTIVE USE

This section describes the actual physical make-up of the input file. This file can be created manually, but the interactive use of the program will also accomplish the task in an error free manner. The details in this section will allow the user to easily modify a file created during interactive usage of the program, or actually create a file from scratch. It is recommended that the interactive method be used at least for the initial description of a radiator design to ensure the data has been input correctly. In this section an input file line (shown in **bold face**) will be expressed with the appropriate variable names, then the options, values, and ramification of certain choices will be described as they relate to the variables. This will serve two purposes. First, it will compliment the information provided below concerning the "walk through" of the program. Second, it will furnish a list of variables that are actually used in the code for calculational and logic purposes. This will aid a user in the determination of the logic involved in many of the algorithms. Two additional things need to be specified. The code uses an unformatted read statement of the input file, therefore, the user does not have to worry about ensuring that certain variables are located in specific columns of the file. The input information must be separated by a comma or a space. Secondly, the code uses an implicit specification for integers and real valued variables. Therefore, any variable beginning with the letters I through N (inclusive) are considered to be integers and must be entered into the input file as such. These variables generally constitute counters and flags within the program structure.

**NOPT,NPAN,FWID,IPANT,DIH,HPERIM,ICOND,M,COEF**

NOPT - Optimization flag variable. NOPT = 0 for non-optimized use of code while NOPT = 1 is to use the algorithm in a mass optimization

manner.

- NPAN - Number of radiator panels per independent transport duct path.
- PWID - Maximum total radiator panel width in meters. Can only be used when NOPT=0. Occurs when a fixed transport duct width will be specified for the radiator (IDES=1; explained below) and this value will be used to determine the heat pipe condenser length. This value will depend on if the heat pipes are specified to emanate from one or two sides of the transport duct.
- IPANT - Type of radiator panel. IPANT=1: heat pipes project from only one side of the transport duct; IPANT=2: heat pipes project from both sides of the transport duct.
- DIH - Primary transport duct effective hydraulic diameter in meters. It is determined from the following equation:
- $$DIH = 4A_c/P_w \quad \text{where } A_c = \text{duct cross-sectional area}$$
- $$P_w = \text{duct wetted perimeter}$$
- HPERIM - Wetted perimeter of primary transport duct in meters.
- ICOND - Fluid phase flag. If ICOND = 0: transport duct fluid is single phase (i.e. all liquid or all gas); ICOND = 1: two-phase fluid is used in the transport duct. Currently, when this option is exercised, a heat transfer coefficient of 15,000 W/m<sup>2</sup>K is used for the condensing vapor. This is due to the fact that a zero-gravity correlation condensing correlation is unknown to the author.
- M - Number of different heat pipe types used in the radiator. A heat pipe type is defined as one in which the working fluid is different. The code is intended to allow the use of several (up to 5) different heat pipe working fluids within on radiator system in order to allow a large transport duct fluid temperature change.
- COEF - Loss coefficient of an independent transport duct network (non-dimensional) for supplemental pressure drop determination.

If the optimization routine is used (NOPT=1), the following lines follow in the input data set:

#### NVAR

- NVAR - This variable indicates which variable is to be used for the mass optimization. The available choices are:
- NVAR = 1; Fin thickness
- NVAR = 2; Fin width (defined as the distance between outside diameter of heat pipes)
- NVAR = 3; Heat pipe redundancy
- NVAR = 4; Heat pipe diameter

NVAR = 5; Variation of number of independent transport ducts  
surviving the entire mission duration

If NVAR = 1, the next lines in the input file will be:

**TFINHI,TFINLO**

These are the upper (TFINHI) and lower (TFINLO) constraints of the fin thickness (in meters) for the optimization. The algorithm will only determine a minimum mass system that has the optimization variable between these values. The line is repeated M (as defined above) times to account for all the different heat pipe types. The variable order is from the highest temperature heat pipe working fluid to the lowest.

If NVAR = 2, then the next lines will appear:

**FWIDHI,FWIDLO**

These are the upper (FWIDHI) and lower (FWIDLO) constraints for the fin width (in meters). As with the fin thickness, the line is repeated M times starting with the high temperature heat pipe conditions.

If NVAR = 3, then the following will appear:

**REDHI,REDLO**

These are the upper (REDHI) and lower (REDLO) constraints of the heat pipe redundancy. It is assumed that all the different heat pipe types will have the same relative amount of redundancy. The values that are to be entered are calculated as follows:

$$RED = 1.0 + \text{Redundancy (in percent)}/100.$$

Therefore, a 5 percent redundancy constraint would be specified by a 1.05 value entered into the input file.

If NVAR = 4, the following is specified:

**DHI,DLO**

These are the upper (DHI) and lower (DLO) constraints of the actual heat pipe diameter in meters. As with the other parameters, it is repeated M times account for the different heat pipe types. It starts with the high temperature pipe and continues to the low.

If NVAR = 5, no additional constraints need be specified. The number of surviving independent transport ducts is automatically varied from 1 up to the maximum number possible. The mass results for all the possible values will appear in the output file.

After the lines for the optimization case (if they are required), the

following will appear:

**HL, ENLT, EXLT, IHLM, HLT, ICONV, LHPLOC**

- HL - Maximum radiator duct length per panel, in meters. To be used when NOPT=0. Occurs when a fixed transport duct length will be specified for the radiator (IDES=1; explained below) and this length will be used to determine the heat pipe spacing. The inlet and outlet lengths of the transport duct are subtracted from this length for each panel, and the heat pipes are then evenly distributed over the remaining duct length. If the IDES=1 option is not exercised, the required transport duct length will be determined for the system based on specified fin width values.
- ENLT - Entrance length of transport duct for each radiator panel that contains no heat pipes (in meters).
- EXLT - Exit length of transport duct for each radiator panel that contains no heat pipes (in meters). The entry and exit lengths of the transport ducts may represent portions of a radiator that are required for some other use such as a deployment mechanism.
- IHLM - Transport duct liner material code flag. See 2.3.2.1 for the associated material flag values. If no liner is to be used, any integer value may be entered.
- HLT - Transport duct liner material thickness in meters. When no liner is used, a value of 0.0 should be specified for the variable.
- ICONV - Flag that specifies the boundary condition on the external radiator surface. ICONV = 0: represents a condition of pure radiative heat transfer from the outside surface; ICONV=1: a combined convective and radiative heat transfer system exists on the radiator surfaces.
- LHPLOC - Flag that specifies the relative location of the heat pipes on the transport duct. LHPLOC=1: the heat pipes protrude into the transport duct and come into physical contact with the duct fluid; LHPLOC=2: the heat pipe is located on the transport duct and is coupled to the duct fluid by conduction through the duct and heat pipe wall. This latter arrangement is the one present on the SP-100 radiator configuration.

If ICONV = 1, the next line will appear:

**HCONV**

This is the external convective heat transfer coefficient that is present on the radiator external surfaces.

**IHAR, IHWF, AQ, TIN, TOUT, IDES, NPARA, NLOSS, NPAN**

- IHAR - Transport duct material code flag. See section 2.3.2.1 for the actual material associated with each variable value.
- IHWF - Transport duct working fluid code flag. Section 2.3.1.1 describes the fluids and their codes available for use in the program.
- AQ - Desired heat transfer of the radiator at the end of life condition in kilowatts.
- TIN - Inlet temperature of the transport duct fluid in K.
- TOUT - Desired outlet temperature of the transport duct fluid in K.
- IDES - Flag that specifies how a radiator design will be developed. This option is not available when the optimization method of analysis is chosen (i.e. NOPT = 2) and the IDES flag should then be set to be equal to 2. When the non-optimized version of the code is used, this variable may be set to equal to 1. When this is the case, it is assumed that severe constraints are to be placed upon the maximum size of the radiator structure. Therefore, both a maximum transport duct length (per panel) and maximum radiator panel width is assumed to be required in the design. These stipulations then allow the program to determine certain variable values that would normally be specified as input by the user when this option is not used. Specifically, the heat pipe condenser length is calculated as the specified panel width (PWID) minus the transport duct diameter. This length would be divided by two if the heat pipes project from both sides of the transport duct. Also, the fin width is determined by subtracting the outside diameters of all the system heat pipes and the lengths of the inlet and outlet sections of the transport ducts from the total transport duct length (accounting for all the radiator panels) and dividing this value by the total number of heat pipes required in the system. Thus, it is assumed the heat pipes and fin will take up all the available duct area. If IDES is set to equal 2, both the fin width and heat pipe condenser length must be specified by the user for each heat pipe type. When IDES=1, all the different heat pipe types will be assumed to have the same condenser length. This may create some out of limit conditions for the heat pipes. The use of the IDES=1 option does have some applications in a design situation, but it is recommended that the program be used with the IDES variable set to equal 2.
- NPARA - Number of independent parallel transport duct paths in the radiator at the beginning of the mission.
- NLOSS - Number of allowable inoperative (due to micro-meteoroid and space debris impact punctures) transport ducts at the end-of-mission configuration.
- NPAN - Number of sections or panels of radiator per each independent parallel path.

If the transport duct fluid was specified to have user defined properties, i.e. an IHWF of 15, the following line will next appear in the input data file:

**CPHF,CONDHF,VISCHF,RHOHL**

- CPHF - Specific heat of the transport duct fluid in J/kgK.
- CONDHF - Thermal conductivity of the transport duct fluid in W/mK.
- VISCHF - Viscosity of the transport duct fluid in N-s/m<sup>2</sup>.
- RHOHL - Density of the transport duct fluid in kg/m<sup>3</sup>.

The following line will then occur either after the NPAN or RHOHL value:

**RPR,TSINK,F1,F2,EMIS,FLOW,ITRANS**

- RPR - Inlet pressure of the transport duct fluid in the radiator. It is used to determine the pressure stresses of the transport duct.
- TSINK - Effective sink temperature the radiator panels experience. To yield a conservatively sized radiator design, this variable should be the maximum value that will be experienced during a mission or an orbit.
- F1 - Effective view factor of side number 1 of the radiator to the effective sink temperature. For the radiator being designed, if the heat pipes are located on (versus in) a transport duct, the two sides of the radiator will not be symmetrical. If this is the case, side 1 is defined as the side of the radiator panel having the transport duct located on it. It should be noted, when the heat pipes are located in the transport duct, this distinction is not applicable.
- F2 - View factor of side 2 of the radiator to the effective sink temperature. This, along with the F1 variable allow for the design of a radiator in nearly any geometry.
- EMIS - The emissivity of the external surfaces of the radiator. All the material that comprises the radiator is assumed to have the same emissivity.
- FLOW - This variable represents the mass flow rate of fluid through the entire transport duct system (i.e. all independent paths) at the beginning of the radiator mission life. This only applies when the fluid in the transport duct is specified as being condensed, (ICOND = 1). If the fluid in the transport duct is single phase, the FLOW variable should be entered as zero. The flow rate is specified in kg/s of fluid. The heat transfer of the system is

then determined by:

$$Q = mh_{fg}$$

m = mass flow

$h_{fg}$  = enthalpy of vaporization

**ITRANS** - This variable specifies whether a return transport duct is included in the radiator system design. If one is to be included, ITRANS = 1 is specified, while ITRANS = 0 assumes no return duct is present in the design. If one is included, a certain amount of it will have to be protected with armoring or bumpering. The main and return ducts are assumed to be located adjacent to one another in the system design. Therefore, they will tend to shield each other from micro-meteoroids and space debris. The actual amount of shielding depends on the shapes of the return and main transport duct. A value of 25% shielding has been assumed for ducts of circular and non-circular cross sections. Therefore, 75% of the total combined area of the normal and return duct are used for the vulnerable area calculation. This is for the assumption of total vulnerable area available for space debris exposure. When a projected area is assumed for this calculation, only half of this value of vulnerable area is used for armor determination on the transport duct for the micro-meteoroid flux.

If a return duct is specified for the system (ITRANS = 1), then the following should be entered on the next data line:

**RETDIH, RETPER**

**RETDIH** - Return transport duct hydraulic diameter in meters.

**RETPER** - Return transport duct wetted perimeter in meters.

The following line will appear after either the data for the return transport duct or after the line ending with the ITRANS variable.

**SURVHP, SURVTD, RED, ALT, IENV, DURR, ADWPP, ADSW**

**SURVHP** - This specifies the required survivability of the heat pipes in the system. This value is used in the determination of the armor thickness of the heat pipe. A typical value would be .95 to represent a 95% probability of the heat pipes survivability.

**SURVTD** - This specifies the required survivability of the transport duct(s) in the radiator system. This value is used in the determination of the armor thickness of the ducts. The variable is specified in the same way as the SURVHP variable. The product of the heat pipe and transport duct survivabilities will yield an overall system survivability value.

- RED - This variable specifies the redundancy to be used for the heat pipes. This variable is also used in the determination of the heat pipe armor thickness. The value entered is determined in the same way the REDHI and REDLO are determined, i.e. a RED value of 1.05 signifies a 5% desired redundancy. It should be noted that for this variable, as well as any other variable that can be optimized, may have any value in the main data deck when it has been chosen for use in the optimization. When the optimizing option is used, the controlling variable are the limits specified for the optimization specified in the third line of the input deck.
- ALT - This is the altitude in kilometers at which the radiator is to operate during its mission. This value helps determine the micro-meteoroid flux that will be experienced during a mission.
- IENV - This variable specifies the environment for the radiator system. If IENV = 1, then only micro-meteoroids are assumed to be present, and the radiator armoring thickness will be calculated based only on this flux. If IENV = 2, space debris will also be considered to be present in the radiator environment.
- DURR - This represents the desired mission life of the system in years.
- ADWPP - This variable is used to add weight to the system. It represents the additional mass (in kg) to be added in the system analysis for each radiator panel present in the entire system. This may be indicative of some structural mass requirement for each panel such as a deployment mechanism required for each panel.
- ADSW - This variable is also used to account for additional masses present in the system that may not be covered by this analysis. This variable represents the extra, lump sum, mass (in kilograms) to be added for the entire radiator system.
- ADWPS, NARN, NAREA, AMPMTD, NMOD, AMULT**
- ADWPS - This variable is also used to add mass to the system. It represents the additional mass (in kilograms) to be added during the analysis for each independent section of the radiator. It may represent, for example, the mass of a pump that would be required for each independent transport duct.
- NARM - This variable represents the choice of armoring design for the transport duct. If NARM = 1, then normal armoring methods are used, while NARM = 2 specifies that offset bumpering techniques be employed. Currently, no bumpering calculations exist, and therefore, NARM should always be specified to be equal to 1.
- NAREA - This flag represents the vulnerable area determination to be used in the armor determination for space debris protection. A NAREA

value of 1 signifies the actual circumferential area is to be used while a NAREA of 2 indicates the projected surface area will be used in determining the vulnerable area of the heat pipes or transport duct. This option was added due to the uncertainty involved in the nature of space debris.

- AMPMTD - This variable also adds mass to the system analysis. It represents the addition of mass (in kilograms) for each meter of transport duct length for each transport duct. It may represent some type of mass adjustment, such as a bumper, for the entire, unknown transport duct length.
- NMOD - This variable is used to specify the model to be used for the armor determination. If NMOD = 1, the NASA Thin model will be used, while NMOD = 2 indicates the NASA Thick model with a correction factor will be used. Section 2.5.2 of this manual discusses the details of these two models.
- AMULT - If the NASA Thick model is used, the AMULT variable specifies the correction factor to be used with it. Currently, the NASA Thick model calculations have a built-in correction value of 1.5. Therefore, the specification of AMULT does not affect it. This will be changed in the future. The recommended range of this value will be 1.5 to 2.5. If the NASA Thin plate model is specified (NMOD=1), then this variable should be set to be zero.

If the material chosen for the transport duct liner is to be user specified (IHLM =7), the next line will follow.

**CONHLM,RHOHLM,HLK1**

- CONHLM - Transport duct liner material thermal conductivity (W/mK).
- RHOHLM - Transport duct liner material density (kg/m<sup>3</sup>).
- HLK1 - Transport duct liner material impact coefficient (as would be used with the NASA Thin plate model).

If the material chosen for the transport duct armor is to be user specified (IHAM =7), the next line will follow.

**CONHAM,RHOHAM,HAK1**

- CONHAM - Transport duct armor material thermal conductivity (W/mK).
- RHOHAM - Transport duct armor material density (kg/m<sup>3</sup>).
- HAK1 - Transport duct armor material impact coefficient (as would be used with the NASA Thin plate model).

The final lines in the program describe the details of the heat pipes to be used in the radiator design. Therefore, there will be M sets of the following data starting with the highest temperature working fluid heat pipe.

**EVAP, DHPA, HPLTE, HPLTC, IHPF, IHPL, IHPA, IWT, FINT, FACTOR**

- EVAP -** This variable is the length (in meters) of the evaporator section of the heat pipe. This is the length of the pipe either in or on the transport duct depending upon the design.
- DHPA -** This variable represents the actual heat pipe diameter (in meters) (assuming the heat pipe is round). This value is used to determine the vulnerable area of the heat pipe. An equivalent diameter can be determined for non-round heat pipe designs.
- HPLTE -** This variable represents the specified thickness (in meters) of the liner material in the evaporator region of the heat pipe. If no liner is to be used, then this value should be set equal to zero.
- HPLTC -** This variable represents the specified thickness (in meters) of the liner material in the condenser region of the heat pipe. If no liner is to be used, then this value should be set equal to zero.
- IHPF -** This variable specifies the fluid used in the particular heat pipe. Section 2.3.1.2 of this manual indicates the fluids available for use and their applicable temperature ranges. The first heat pipe (and fluid) specified should be able to be used at the radiator inlet temperature. If the fluid can not cover the entire temperature range required for the radiator, additional heat pipes and fluids will have to be specified in the input deck.
- IHPL -** This flag specifies the liner material choice for the heat pipe. Section 2.3.2.1 indicates the choices available for the materials. If no liner is to be used, this should be set equal to be zero.
- IHPA -** This flag specifies the armor material choice for the heat pipe. Section 2.3.2.1 indicates the choices available for the materials.
- IWT -** This variable identifies the wick design for the heat pipe. The following choices are available:
- IWT = 1 - Rectangular grooves
  - IWT = 2 - Screen wick
  - IWT = 1 - Sintered metal wick
  - IWT = 1 - Generic wick described by user properties
  - IWT = 1 - Screen wick with arteries
  - IWT = 1 - Sintered metal wick with arteries
- FINT -** This is the thickness (in meters) of the fin attached to the heat pipe. If the fin thickness is to be optimized, then this variable

should be set equal to zero.

**FACTOR -** This variable represents a multiplicative factor to be used on the available heat transfer area on the heat pipe evaporator section. This allows for adding augmentation to the outside of the heat pipe evaporator (which would come into contact with the transport duct fluid). It may be used in such a case when a gas with a low heat transfer coefficient is being used as the transport duct medium. Then, fin material may be desired to be added to the external evaporator area in order to reduce this thermal resistance. If no augmentation is desired, a value of one should be specified for FACTOR.

#### **IWM,DHP,IFIN**

**IWM -** This variable specifies the wick material flag. Section 2.3.2.1 indicates the material associated with the various values of IWM.

**DHP -** This variable specifies the diameter (in meters) of the heat pipe that will be used for the thermal/hydraulic calculations. For round heat pipes, this will have the same value as the DHPA variable, but for non-round designs, they may be substantially different.

**IFIN -** This flag specifies the material to be used for the fins. Section 2.3.2.1 indicates the available choices of material.

If the IDES variable is equal to two (by user choice or by default when running an optimization design), the following line will next appear in the data deck.

#### **FINW,HPCL**

**FINW -** This variable is the fin width (in meters). Fin width is defined to be the distance between adjacent heat pipes (i.e. outside surface to outside surface).

**HPCL -** This variable represents the heat pipe condenser length (in meters).

If the heat pipe liner material is to be of a user specified material, (IHPL = 7), then the following line is required.

#### **CONDL,HPRHOL,HPLK1**

**CONDL -** Heat pipe liner material thermal conductivity (W/mK).

**HPRHOL -** Heat pipe liner material density (kg/m<sup>3</sup>).

**HPLK1 -** Heat pipe liner material impact coefficient (as would be used with the NASA Thin plate model).

If the heat pipe armor material is to be of a user specified material, (IHPA = 7), then the following line is required.

**CONDA,HPRHOA,HPAK1**

- CONDA - Heat pipe armor material thermal conductivity (W/mK).  
HPRHOA - Heat pipe armor material density (kg/m<sup>3</sup>).  
HPAK1 - Heat pipe armor material impact coefficient (as would be used with the NASA Thin plate model).

If the fin material is to be of from user specified properties (IFIN =7), the following line will have to appear:

**CONDF,RHOFIN**

- CONDF - Heat pipe fin material thermal conductivity (W/mK).  
RHOFIN - Heat pipe fin material density (kg/m<sup>3</sup>).

The following lines describe the wick details for the particular heat pipe design. Additional details about the required inputs can be obtained from the authors of Reference 9. This section of the code was taken directly from that work.

If IWT = 1 (Rectangular Groove), one line is required to describe the wick:

**DEEP,WIDGRV,NUM**

- DEEP - Depth of the rectangular grooves (in meters).  
WIDGRV - Width of the rectangular grooves (in meters).  
NUM - Number of rectangular grooves around the periphery of the heat pipe. Note, the number and size of grooves can not exceed the available circumference length (i.e.  $NUM \times WIDGRV < \pi \times (DHP - 2(DEEP))$ ).

If IWT = 2 (Screen Wick), one line is required to describe the wick:

**DIAM,WIDE,CRIMP,NUMWRP**

- DIAM - Screen wick wire diameter (in meters).  
WIDE - Center to center spacing between wick wires (in meters).  
CRIMP - Crimping factor of screen wire wick.

NUMWRP - Number of wraps of screen specified for the wick design.

If IWT = 3 (Sintered Metal), one line is also required for the data:

**TWICK,PORW,RSS**

TWICK - Thickness of the sintered metal wick (in meters).

PORW - Porosity of the wick structure. A PORW value of 0.50 indicates a 50% porous wick structure.

RSS - Average radius of the sintered particles which comprise the wick structure (in meters).

If IWT = 4 (User Input Wick Properties) then five lines of data are required:

**AKE,AKC,PE**

AKE - This variable represents the product of the evaporator wick permeability and the wick area ( $m^4$ ).

AKC - This variable represents the product of the condenser wick permeability and the wick area ( $m^4$ ).

PE - This is the value of the inner perimeter of the heat pipe in the evaporator section (for thermal/hydraulic calculations not for armor determination) in meters.

**PORE,PORC,AKEE**

PORE - This variable is the porosity of the wick structure in the heat pipe evaporator section. It should be entered into the data deck in decimal form (i.e. 0.50 = 50% porosity).

PORC - This variable is the porosity of the wick structure in the heat pipe condenser section. It should be entered into the data deck in decimal form (i.e. 0.50 = 50% porosity).

AKEE - This represents the evaporator effective wick thermal conductivity ( $W/m^2 K$ ).

**AKEC,AVE,AVC**

AKEC - This represents the effective wick thermal conductivity in the condenser section of the heat pipe ( $W/m^2 K$ ).

AVE - This is the effective vapor area available in the heat pipe evaporator section (in  $m^2$ ).

AVC - This is the effective vapor area available in the heat pipe condenser section (in m<sup>2</sup>).

**RCM,DCRITE,RATAR**

RCM - This variable is the maximum meniscus radius available in the heat pipe wick structure (in meters).

DCRITE - This is the value of the critical entrainment dimension in the heat pipe evaporator wick (in meters).

RATAR - This variable represents the ratio of the inside area of the evaporator to its open area.

**AREAWC,AREAWC**

AREWE - This represents the actual cross sectional area of the wick structure in the evaporator of the heat pipe. It, along with the porosity are used to determine the mass of the wick in the heat pipe evaporator region.

AREAWC - This represents the actual cross sectional area of the wick structure in the condenser section of the heat pipe. It, along with the porosity are used to determine the mass of the wick in the heat pipe condenser section.

When IWT = 5 (Screen wick with arteries), two lines of data are required. The first is the same required for the screen wick alone:

**DIAM,WIDE,CRIMP,NUMWRP**

The second line describes the arteries:

**RA,AWT,NA**

RA - Radius of arteries in the wick (in meters).

AWT - Thickness of the artery wall (in meters).

NA - Number of arteries in the wick structure.

If IWT = 6 (Sintered Metal wick with arteries), two lines of data are also required. The first one is the same as the sintered metal wick:

**TWICK,PORW,RSS**

The second line describes the arteries:

### RA,WICCON,NA

- RA - Radius of arteries in the wick (in meters).
- WICCON - Thermal conductivity experimental constant. For metal or felt fiber, a WICCON value of 0.34 should be specified. If sintered particles are used, a value of 0.53 is to be specified.
- NA - Number of arteries in the wick structure.

The final line required for the heat pipe definition is then:

### RN,THETA,WEBNUM

- RN - Minimum nucleation radius of heat pipe envelope material (in meters). A suggested value of this variable is  $1 \times 10^{-6}$  meters.
- THETA - This represents the wetting angle between the heat pipe fluid and wick material (in degrees).
- WEBNUM - This represents the Weber number at the onset of entrainment for the particular heat pipe.

This completes the data required for analyzing or designing a radiator. If additional heat pipes are required for the design, the data on the line starting with the EVAP variable would next be entered. The data would continue until the heat pipe fluid is capable of operating at the radiator outlet temperature.

### 3.2.2

### INTERACTIVE USAGE

This section describes the questions that are used to query the user for a response during interactive use of the program. Even though it is highly recommended that this approach be used (at least initially) to create the data file for an analysis, it was decided to first describe the actual data deck that is required for the program before the actual interactive details are provided (refer to section 3.2.1). This section is meant to compliment the previous one. The actual questions that appear during the use of the program will appear in bold faced type. Then, the variable being triggered by the response will be identified as will any results of the particular variable choice. The description of the variables discussed can be obtained from section 3.2.1.

Both the optimized and non-optimized version of the code as well as their usage and interactive input requirements will be addressed in this section. The optimized approach will be addressed initially.

IS THE DATA FOR THIS RUN CURRENTLY IN AN EXISTING DATA FILE ? (Y/N)

Answering "N" to this question automatically invokes the interactive usage of the code. By responding with a "Y", the program then asks for the data file name, and then proceeds to use that file for the analysis.

OPTIMIZATION CHOICES: (ENTER 1 OR 2)

1. MINIMUM MASS OPTIMIZATION RUN
  2. UNOPTIMIZED, SIMPLE MASS DETERMINATION RUN
- ENTER 1 or 2:

Variable triggered - NOPT

If optimization is chosen the following will appear:

DESIRED SYSTEM PARAMETER TO BE VARIED:

1. FIN THICKNESS
  2. FIN WIDTH
  3. SYSTEM REDUNDANCY
  4. HEAT PIPE DIAMETER(S)
  5. NUMBER OF PANELS SURVIVING
- ENTER CHOICE:

Variable triggered - NVAR

SYSTEM PARAMETERS:

TOTAL HEAT REJECTION REQUIRED (kW):

Variable triggered - AQ

RADIATOR INLET TEMPERATURE (K):

Variable triggered - TIN

RADIATOR OUTLET TEMPERATURE (K):

Variable triggered - TOUT

RADIATOR INLET PRESSURE (kPa):  
(FOR STRESS CALCULATION PURPOSES)

Variable triggered - RPR

IS CONDENSATION PRESENT IN THE TRANSPORT DUCT (Y/N) ?

Variable triggered - ICOND

If condensation is present, the following will appear:

**TOTAL SYSTEM MASS FLOW RATE OF CONDENSING FLUID AVAILABLE (kg/s):**  
(i.e. BEGINNING OF LIFE)

Variable triggered - FLOW

**SINK TEMPERATURE (K):**

Variable triggered - TSINK

**VIEW FACTOR OF SIDE 1 TO SINK:**  
**NOTE: SIDE 1 IS DEFINED AS THE SIDE WITH THE TRANSPORT DUCT WHEN THE HEAT PIPES ARE ON, NOT IN, THE DUCT ENTER VALUE**

Variable triggered - F1

**VIEW FACTOR OF SIDE 2 TO SINK:**

Variable triggered - F2

**EMISSIVITY OF EXTERNAL SURFACES:**

Variable triggered - EMIS

**SURVIVABILITY INFORMATION:**  
**HEAT PIPE SURVIVABILITY PROBABILITY (Z):**

Variable triggered - SURVHP  
Note - in the interactive case, a percent value is entered.

**TRANSPORT DUCT SURVIVABILITY PROBABILITY (Z):**

Variable triggered - SURVTD

If redundancy is to be optimized, the following will appear:

**LOWER BOUND FOR REDUNDANCY IN ANALYSIS (Z):**

Variable triggered - REDLO

**UPPER BOUND FOR REDUNDANCY IN ANALYSIS (Z):**

Variable triggered - REDHI

If redundancy is not to be optimized, the following will appear instead:

**PERCENT REDUNDANCY DESIRED:**

Variable triggered - RED  
Note - this is entered in percent also.

**EARTH ORBIT ALTITUDE (km):**

Variable triggered - ALT

**ENVIRONMENT:**

1. MICRO-METEORIDS
  2. MICRO-METEORIDS AND SPACE DEBRIS
- ENTER CHOICE:

Variable triggered - IENV

**MISSION DURATION (YEARS):**

Variable triggered - DURR

**PENETRATION MODEL TO USE:**

1. NASA THIN MODEL
  2. NASA THICK MODEL WITH AN ADJUSTMENT FACTOR
- ENTER CHOICE:

Variable triggered - NMOD

If the NASA Thick model is chosen, the next line will appear:

**DESIRED MULTIPLICATIVE FACTOR (RECOMMENDED RANGE 1.5 TO 2.5):**

Variable triggered - AMULT

**AREA USED TO CALCULATE VULNERABLE AREA FOR SPACE DEBRIS IMPACT:**

1. ACTUAL, CIRCUMFERENTIAL AREA
  2. PROJECTED AREA
- ENTER CHOICE:

Variable triggered - NAREA

**IS THERE CONVECTION ON THE RADIATOR EXTERNAL SURFACES (Y/N) ?**

Variable triggered - ICONV

If there is to be convection, the following line will appear:

**ENTER CONVECTIVE HEAT TRANSFER COEFFICIENT (W/m\*\*2 K)**

Variable triggered - HCONV

**TRANSPORT DUCT INFORMATION:**

**TYPE OF TRANSPORT DUCT:**

1. HEAT PIPES PROJECT TO ONLY ONE SIDE
  2. HEAT PIPES PROJECT IN TWO DIRECTIONS
- ENTER 1 or 2:

Variable triggered - IPANT

**TRANSPORT DUCT/HEAT PIPE CONFIGURATION:**

1. HEAT PIPE PROTRUDES INTO TRANSPORT DUCT
2. HEAT PIPE IS LOCATED ON TRANSPORT DUCT

ENTER 1 or 2:

Variable triggered - LHPLOC

**IS THERE TO BE A RETURN DUCT ON THE TRANSPORT DUCT (Y/N) ?**

Variable triggered - ITRANS

**TRANSPORT DUCT PROTECTION SCHEME:**

1. NORMAL ARMORING PROCEDURES
2. OFFSET BUMPERING IS TO BE USED

ENTER CHOICE:

Variable triggered - NARM

Note - only choice #1 is currently allowed

**TOTAL NUMBER OF PARALLEL PATHS:**

Variable triggered - NPARA

If the number of transport ducts surviving is not to be optimized, the following line will appear.

**NUMBER OF ALLOWABLE PATH LOSSES**

Variable triggered - NLOSS

**TRANSPORT DUCT(S) EFFECTIVE HYDRAULIC DIAMETER (m):**

Variable triggered - DIH

**TRANSPORT DUCT WETTED PERIMETER (m):**

Variable triggered - HPERIM

If a return duct is to be used in the analysis, the following two lines will appear:

**RETURN TRANSPORT DUCT(S) EFFECTIVE HYDRAULIC DIAMETER (m):**

Variable triggered - RETDIH

**RETURN TRANSPORT DUCT WETTED PERIMETER (m):**

Variable triggered - RETPER

**ESTIMATE OF TRANSPORT DUCT(S) LOSS COEFFICIENTS (PER PANEL):**

Variable triggered - COEF

**PANEL INFORMATION:**

**NUMBER OF PANELS IN RADIATOR (PER PARALLEL TRANSPORT DUCT PATH):**

Variable triggered - NPAN

If the non-optimized version of the code is being used, the following line will appear:

1. DESIGN OF RADIATOR TO BE BASED ON COMPUTER GENERATED TUBE SPACING (i.e. FIXED TRANSPORT DUCT LENGTH w/ NO OPTIMIZATION)
2. USER SPECIFIED FIN WIDTH

Variable triggered - IDES

If IDES = 1 is specified, the following two lines will appear:

**MAXIMUM PANEL WIDTH (m):**  
**(TO BE USED TO DETERMINE CONDENSER LENGTH)**

Variable triggered - PWID

**MAXIMUM TRANSPORT DUCT LENGTH PER PANEL (m):**

Variable triggered - HL

**INLET LENGTH OF TRANSPORT DUCT(S) (m):**

Variable triggered - ENLT

**OUTLET LENGTH OF TRANSPORT DUCT(S) (m):**

Variable triggered - EXLT

**TRANSPORT DUCT LINER THICKNESS (m):**

Variable triggered - HLT

If there is to be a liner, the following will appear:

**TRANSPORT DUCT LINER MATERIAL:**

**NOTE: CHOICES 8 THROUGH 14 WILL OFFER NO STRENGTH FOR MICRO-METEOROID/ DEBRIS PROTECTION IN CALCULATIONS**

A list of material choices will then appear. The user should respond by entering the number of the material chosen.

Variable triggered - IHLM

If the material choice is the user specified material, the following three lines will appear:

**THERMAL CONDUCTIVITY (W/mK):**

Variable triggered - CONHLM

**DENSITY (kg/m3):**

Variable triggered - RHOHLM

**THRESHOLD PENETRATION CONSTANT:**

Variable triggered - HLK1

**TRANSPORT DUCT ARMOR/BUMPER MATERIAL:**

A list of materials will then appear. The user should respond by entering the number of the material chosen.

Variable triggered - IHAR

If the material choice is the user specified material, the following three lines will appear:

**THERMAL CONDUCTIVITY (W/mK):**

Variable triggered - CONHAM

**DENSITY (kg/m3):**

Variable triggered - RHOHAM

**THRESHOLD PENETRATION CONSTANT:**

Variable triggered - HALK1

**TRANSPORT DUCT WORKING FLUID:**

A list of fluid choices will then appear.

Variable triggered - IHWF

If the fluid choice is the user specified material, the following four lines will appear:

**DENSITY (kg/m3):**

Variable triggered - RHOHL

**THERMAL CONDUCTIVITY (W/mK):**

Variable triggered - CONDFH

**FLUID VISCOSITY (Ns/m\*\*2):**

Variable triggered - VISCHF

**FLUID SPECIFIC HEAT (J/kg):**

Variable triggered - CPHF

**HEAT PIPE INFORMATION:**

At this point, all the heat pipe information is going to be determined. Initially, a menu will appear indicating the available fluids that may be used for the heat pipes in the temperature range of interest. Also appearing will be the range of temperature over which the various heat pipe fluids are applicable. For example, if the inlet temperature of the transport duct is 850 K, the following menu will appear:

1. POTASSIUM (RANGE 773 K TO 1273 K)
4. CESIUM (RANGE 723 K TO 1173 K)
6. MERCURY (RANGE 523 K TO 923 K)

The user should specify the fluid choice by entering the number of the desired fluid, e.g. enter 4 for cesium.

Variable triggered - IHPF

If the heat pipe diameter is to be optimized during the analysis, the following two lines will appear:

**LOWER BOUND OF ACTUAL HEAT PIPE INSIDE DIAMETER (FOR OPTIMIZATION) (m):**

Variable triggered - DLO

**UPPER BOUND OF ACTUAL HEAT PIPE INSIDE DIAMETER (FOR OPTIMIZATION) (m):**

Variable triggered - DHI

The following note also appears for this optimization. It instructs the user to enter all the additional data concerning this heat pipe as it pertains to the lower bounds of the optimization. In other words, if it is desired to optimize a heat pipe between 0.005 m and 0.05 m diameter, then all the wick details and other heat pipe characteristics should reflect the 0.005 m diameter design.

**NOTE: THE OPTIMIZATION BASED ON HEAT PIPE DIAMETER USES A SIMPLE RATIOING TECHNIQUE. THE FOLLOWING PARAMETER VALUES ARE TO BE THOSE ASSOCIATED WITH THE LOWER OPTIMIZATION POINT HEAT PIPE INSIDE DIAMETER VALUE.**

The heat pipe diameter optimization has a direct effect of the wick design. As the code currently stands, the only type of heat pipe wick currently available for optimization is the rectangular groove design. Additional work needs to be done to add the other heat pipe wick characteristics to the optimization routine.

If the heat pipe diameter is not to be optimized, the following line will appear:

**ACTUAL HEAT PIPE INSIDE DIAMETER (m):**

Variable triggered - DHPA

The following additional information is then required for each heat pipe:

**HEAT PIPE INSIDE DIAMETER FOR WICK THERMAL/HYDRAULIC CALCULATIONS (m):**

Variable triggered - DHP

**LINER MATERIAL:**

**HEAT PIPE LINER MATERIAL THICKNESS IN EVAPORATOR (m):**

Variable triggered - HPLTE

**HEAT PIPE LINER THICKNESS IN CONDENSER (m):**

Variable triggered - HPLTC

If there is to be a liner, then the following lines will appear:

**HEAT PIPE LINER MATERIAL:**

**NOTE: CHOICES 8 THROUGH 14 WILL OFFER NO STRENGTH FOR MICRO-METEOROID/DEBRIS PROTECTION IN CALCULATIONS**

A list of material choices will then appear. The user should respond by entering the number of the material chosen.

Variable triggered - IHPL

If the material choice is the user specified material, the following three lines will appear:

**THERMAL CONDUCTIVITY (W/mK):**

Variable triggered - CONDL

**DENSITY (kg/m<sup>3</sup>):**

Variable triggered - HPRHOL

**THRESHOLD PENETRATION CONSTANT:**

Variable triggered - HPLK1

Then, the armoring information will be obtained:

**ARMOR MATERIAL:**

A list of material choices will then appear. The user should respond by entering the number of the material chosen.

Variable triggered - IHPA

If the armor material choice is the user specified material, the following three lines will appear:

**THERMAL CONDUCTIVITY (W/mK):**

Variable triggered - CONDA

**DENSITY (kg/m<sup>3</sup>):**

Variable triggered - HPRHOA

**THRESHOLD PENETRATION CONSTANT:**

Variable triggered - HPAK1

If the fin thickness is to be optimized, the following two lines appear next:

**LOWER BOUND OF FIN THICKNESS (FOR OPTIMIZATION) (m):**

Variable triggered - TFINLO

**UPPER BOUND OF FIN THICKNESS (FOR OPTIMIZATION) (m):**

Variable triggered - TFINHI

If fin thickness is not being optimized, the following line will appear:

**FIN INFORMATION:**

**WHAT IS THE FIN THICKNESS (m):**

Variable triggered - FINT

**FIN MATERIAL:**

A list of material choices will then appear. The user should respond by entering the number of the material chosen.

Variable triggered - IFIN

If the fin material choice is the user specified material, the following two lines will appear:

**THERMAL CONDUCTIVITY (W/mK):**

Variable triggered - CONDF

**DENSITY (kg/m<sup>3</sup>):**

Variable triggered - RHOFIN

If the fin width is to be optimized, the following two lines will appear:

**FIN WIDTH IS DEFINED IN THIS CASE TO BE THE DISTANCE BETWEEN ADJACENT HEAT PIPES.**

**LOWER BOUND OF FIN WIDTH (FOR OPTIMIZATION) (m):**

Variable being triggered - FWIDLO

**UPPER BOUND OF FIN WIDTH (FOR OPTIMIZATION) (m):**

Variable being triggered - FWIDHI

If fin width is not being optimized, the following will appear:

**FIN WIDTH IS DEFINED IN THIS CASE TO BE THE DISTANCE BETWEEN ADJACENT HEAT PIPES.**

**ENTER FIN WIDTH (m):**

Variable being triggered - FINW

If the condenser length can be specified, (IDES=1), then the following will appear:

**CONDENSER LENGTH (m):**

Variable being triggered - HPCL

The heat pipe wick and evaporator characteristics will now be determined.

**EVAPORATOR LENGTH IN, OR ON TRANSPORT DUCT (m):**

Variable being triggered - EVAP

**EVAPORATOR AREA MULTIPLICATIVE FACTOR:**

Variable being triggered - FACTOR

**WICK TYPES:**

1. GROOVE
2. SCREEN WICK
3. SINTERED METAL
4. USER INPUT WICK CHARACTERISTICS
5. SCREEN WITH ARTERIES
6. SINTERED METAL WITH ARTERIES

**ENTER CHOICE:**

Variable being triggered - IWT

The next thing that will appear will depend on the wick design chosen:

If the rectangular groove design is chosen, the following three lines will appear:

**RECTANGULAR GROOVE DEPTH (m):**

Variable being triggered - DEEP

**RECTANGULAR GROOVE WIDTH (m):**

Variable being triggered - WIDGRV

**NUMBER OF WICK GROOVES:**

Variable being triggered - NUM

If either the screen wick or the screen wick with arteries is chosen, the following four lines will appear:

**SCREEN WICK WIRE DIAMETER (m):**

Variable being triggered - DIAM

**SPACE BETWEEN WICK WIRES (m):**

Variable being triggered - WIDE

**CRIMPING FACTOR:**

Variable being triggered - CRIMP

**NUMBER OF SCREEN WRAPS:**

Variable being triggered - NUMWRP

If the screen wick with arteries is specified, the following three additional lines will also appear:

**ARTERY RADIUS (m):**

Variable being triggered - RA

**ARTERY WALL THICKNESS (m):**

Variable being triggered - AWT

**NUMBER OF ARTERIES:**

Variable being triggered - NA

If either the sintered metal wick or the sintered metal wick with arteries is chosen, the following three lines will appear:

**THICKNESS OF WICK (m):**

Variable being triggered - TWICK

**POROSITY OF WICK (%):**

Note, in the interactive usage of the program, this should be entered as a percent value, i.e. a value of 50 would indicate a 50% porous wick structure.

Variable being triggered - PORW

**RADIUS OF WICK PARTICLES (m):**

Variable being triggered - RSS

If the sintered metal wick with arteries is specified, the following three additional lines will also appear:

**ARTERY RADIUS (m):**

Variable being triggered - RA

**NUMBER OF ARTERIES:**

Variable being triggered - NA

**THERMAL CONDUCTIVITY EXPERIMENTAL CONSTANT**

METAL FELT OR FIBER    C = 0.34  
SINTERED POWDERS      C = 0.53

**ENTER VALUE:**

Variable being triggered - WICCON

If the wick design is to be derived from user specified properties, then the following lines will appear:

**EVAPORATOR WICK PERMEABILITY \* WICK AREA (m\*\*4):**

Variable being triggered - AKE

**CONDENSER WICK PERMEABILITY \* WICK AREA (m\*\*4):**

Variable being triggered - AKC

**EVAPORATOR INNER PERIMETER (m):**

Variable being triggered - PE

**EVAPORATOR WICK POROSITY (Z):**

Variable being triggered - PORE

**CONDENSER WICK POROSITY (Z):**

Variable being triggered - PORC

Note, the above two values are to be entered as a percent. They will be transformed into a decimal value within the program.

**EVAPORATOR EFFECTIVE WICK THERMAL CONDUCTIVITY (W/m\*\*2 K):**

Variable being triggered - AKEE

**CONDENSER EFFECTIVE WICK THERMAL CONDUCTIVITY (W/m\*\*2 K):**

Variable being triggered - AKEC

**EVAPORATOR EFFECTIVE VAPOR AREA (m\*\*2):**

Variable being triggered - AVE

**CONDENSER EFFECTIVE VAPOR AREA (m\*\*2):**

Variable being triggered - AVC

**MAXIMUM MENISCUS RADIUS (m):**

Variable being triggered - RCM

**EVAPORATOR ENTRAINMENT CRITICAL DIMENSION (m):**

Variable being triggered - DCRITE

**EVAPORATOR INSIDE AREA / OPEN AREA:**

Variable being triggered - RATAR

**WICK CROSS SECTIONAL AREA IN EVAPORATOR (m\*\*2):**

Variable being triggered - AREAWE

**WICK CROSS SECTIONAL AREA IN CONDENSER (m\*\*2):**

Variable being triggered - AREAWC

Then, some basic information required for all the different wick structures will appear:

**MINIMUM NUCLEATION RADIUS (m):**  
**DEFAULT VALUE = 1.0E-6**

Variable being triggered - RN

**WETTING ANGLE:**

Variable being triggered - THETA

**WEBER NUMBER AT ONSET OF ENTRAINMENT:**

Variable being triggered - WEBNUM

If the heat pipe fluid chosen is capable of covering the entire temperature range of the radiator, then the lines shown below will appear. However, if the heat pipe fluid's lowest applicable temperature is greater than the desired radiator outlet temperature, additional choices of heat pipe fluids will appear, and after that, the details required for the heat pipe design and analysis. For example, in the above design, an 850 K inlet temperature was specified and cesium was chosen as the heat pipe fluid. If a radiator outlet temperature of 450 K is desired, the cesium will not be able to cover the entire temperature range. Its lowest applicable temperature is 773 K. Therefore, additional fluid(s) will be required. What will appear next will be choices for the next heat pipe fluid to cover more of the temperature range. After that, the detailed information concerning the design of the second heat pipe will be obtained.

If this second fluid's temperature range is low enough to meet the radiator outlet temperature, then the system mass information questions shown below will appear. Otherwise, the process will begin again with new fluid choices and will continue until enough have been chosen to cover the entire radiator temperature range. As the computer code now stands, a maximum of five different heat pipe fluids may be specified for a radiator design. The fluids available cover a temperature range of 213 K to 2073 K. Therefore, it is anticipated all radiator designs can be accommodated with this choice of fluids. The algorithm was set up this way to allow the design and analysis of radiators for Brayton cycles which will typically require a large temperature change of the transport duct fluid.

**SYSTEM MASS INFORMATION:**  
**ADDITIONAL MASS PER PANEL TO BE ADDED (kg):**

Variable triggered - ADWPP

**ADDITIONAL MASS PER METER OF TRANSPORT DUCT(S) (kg/m):**

Variable triggered - AMPMTD

**ADDITIONAL MASS PER SECTION (PARALLEL PATH) TO BE ADDED (kg):**

Variable triggered - ADWPS

**ADDITIONAL SYSTEM MASS TO BE ADDED (kg):**

Variable triggered - ADSW

The following lines are then used to determine in what file the data just entered will be stored.

**THIS DATA WILL BE WRITTEN TO A FILE  
WHAT DO YOU WISH THIS NEW FILE TO BE CALLED ?**

If for some reason, an error is encountered in the specified data during calculations, the user will still have the data entered stored in a file. Next, the user is prompted to determine which file shall receive the output information.

**NAME OF FILE TO PRINT OUTPUT TO:**

At this time, the computational procedure begins. If an error occurs, it is recommended that the output file be examined to determine how far the program progressed. The next section describes the code output.

## 4.0 CODE OUTPUT

### 4.1 INTRODUCTION

This section of the user's manual will describe the output that can be expected from using the code. All the flags and descriptors are explained in detail. An example is furnished to aid in this task. It is representative of what can be obtained from using this analysis tool with both the optimizing analysis and non-optimizing version of the code.

### 4.2 DESCRIPTION

Very little difference exists between the output obtained from using the code in an optimized and non-optimized configuration. The difference will be seen at the very beginning of the output. The non-optimized output begins with a starred(\*\*\*) heading while the optimization begins with the results of calculational steps made in order to determine the system minimum mass. This can be seen on the attached example. In the optimized version of the code, prior to the starred header, lines will exist that show the optimization variable call NVAR. This indicates which variable was used to obtain the minimum mass radiator design. The variable value is the same as defined above in the input deck description.

After the NVAR variable is the actual value of the variable being optimized. The last entry on the line is then the mass determined for the system based on the variable value used in the analysis. Additional lines similar to this follow which show similar results for different values of the optimizing variable. The mass shown should be decreasing as the optimized design is refined. It should be noted, the calculated radiator mass may in fact increase slightly as the optimization calculations proceed. This is a nuance that was discovered using the version of Brent's method taken from Reference 17. It is due to the convergence criteria that is internally specified in the code to control the extent of the optimization. Therefore, the total absolute minimum mass radiator design may not result, but one that is within less than 1% of the minimum value will be obtained. If it is seen that the minimum mass system was not obtained, enough information is available during the optimization analysis to allow the user to choose the correct value for analysis with non-optimized version of the code. It should be noted that the last printed value of the optimized variable is used as the basis of the entire radiator design and all the subsequent information printed.

After all the optimizing analysis printout is complete, a starred header will appear indicating the total results of the analysis just completed. All the information printed from this point on, aside from one small section, will then be the same for the optimizing and non-optimizing versions of the code. If the optimizing version is used, the only difference in the output (from the starred heading on) will appear at the very beginning. Some statements will appear that indicate the optimizing version of the code was used, and it will indicate the variable that was optimized as well as the user imposed limits on the variable chosen.

For the remaining information, user specified requirements and input will be intermixed with code calculated values in order to give a description of the resultant system design. The first (non-optimized use) or second (optimized use) thing to appear will be the basic radiator specifications. These include mission requirements and radiator design choices. For example, the temperature change and heat transfer requirements of the radiator are printed as are view factors, survivability information, and the details of the radiator design. Next are the details about the transports ducts including materials and fluids chosen as well as basic sizes. Additionally, the relative position of the heat pipes and transport duct as well as compatibility information is furnished here.

After the transport duct information appears, all the heat pipe information is provided. This includes the basic specified design as well as the results of the number of the heat pipes required for each panel in the radiator. Additionally, masses and thicknesses are furnished. After all this has been provided for the heat pipes, the overall system results are furnished. This includes the breakdown of the heat transfer and mass associated with each section of the radiator as well as the entire system. Additionally, since radiators are compared based on specific mass ( $\text{kg/m}^2$ ) and specific power ( $\text{kW/kg}$ ), these values are also printed. Several different specific area values are provided due to the many different ways in which this variable can be defined. These are furnished as system and heat pipe values in order to provide an estimate of the contribution of the various components to the system mass and design.

The final information printed is a calculated value of equivalent temperatures (based on an area, sink temperature, and heat transfer) as well as actual surface temperatures experienced by the heat pipes. The estimate of the pressure stresses in the system is provided.

It is felt that the output provides a substantial amount of information for the radiator or system designer to use in the development of a concept that could be carried on to a more detailed TRAYSIS or SINDA level of analysis.

#### 4.3 ERROR MESSAGES

It is hoped that no errors will occur when this program is being used. However, certain constraints do exist that cause some out of tolerance conditions to occur. These will cause the program to terminate its operation. The following are error conditions currently built into the code:

##### 1) Violation of heat pipe limits

Heat pipes may only operate within certain prescribed limits for the fluids and wick structures described. Therefore, circumstances may allow conditions to indicate a heat pipe limit has been violated. If the program is being used in the non-optimized mode a statement will be printed out indicating which heat pipe limit has been violated on which heat pipe type. If an optimization is being performed, an artificial mass (value of  $1\text{E}8$ ) will

be specified for the radiator condition and the program will continue to run. By only allowing the choice of the heat pipe working fluids within the temperature ranges specified in Section 2.3.1.2, the possibility of a heat pipe violating one of its limits is substantially reduced.

## 2) Material incompatibilities

This flag does not affect the execution of the program. It is simply an output line to flag the designer of a possible problem with the materials chosen for the analysis.

## 3) Problem with fin efficiency parameters

The gray body analysis done for the determination of the fin and heat pipe efficiencies relies on non-dimensional parameters that depend on the fin and surface size characteristics as well as their temperature. The data entered into the program to furnish this information is limited. Therefore, it is possible that the size and temperature of the heat pipe being designed will fall outside the tabulated data range. If this occurs during the non-optimized use of the program, statements will appear indicating that the "Fin or Surface Efficiency Data is out of Tabulated Range". The user will have to change some of the fin variables to rerun the program. The range of allowable non-dimensional values used is as follows:

$$0.75 < \epsilon < 0.99$$

$$0.0 < L_2 \sigma T_3 / k_{fin} t_{fin} < 4$$

$$0.025 < R/L < 20$$

where

- $\epsilon$  = material emissivity
- $L$  = distance between adjacent heat pipes' outer surfaces
- $\sigma$  = Stefan-Boltzman constant
- $T$  = outside temperature of heat pipe condenser section
- $k_{fin}$  = fin material thermal conductivity
- $t_{fin}$  = fin thickness
- $R$  = heat pipe radius

As with the heat pipe violations, during the optimization version of the code, this error will only cause an artificial high mass to be specified in the analysis. It has been determined that an optimal fin size should be well within these variables for any analysis performed.

## 4.4 PROGRAM APPEARANCE DURING EXECUTION

Certain other features have also been built into the code to allow the user to track the calculations as the program runs on the computer. This, first, ensures that the code is operating properly, and second, allows user termination of the analysis if something is incorrect. The non-optimizing and optimizing versions of the code will appear different (on the terminal screen)

when they are running. Different information is being provided to track the progress of the analysis.

When the non-optimized version of the code is being used, the actual number of heat pipes calculated to meet the system requirements will be printed on the screen. The user should be able to follow the progress of the code in its determination of the actual required number of heat pipes for the system. With each iteration, the user should see the number of heat pipes closing in on a particular value. If this is not seen within 8 to 10 iterations, the program should be terminated and the input deck examined. It should be noted that work with the program has indicated the possibility of the calculations flip-flopping between two values of the program solution that are very near each other due to the fact that the number of heat pipes has to be rounded to a whole number value. This has been addressed in the program algorithm and should not appear to the user to occur more than two times during the calculations. If it does, the program should be terminated.

When the program is used in the optimizing mode, more information is printed out. This includes the number of the heat pipe section being analyzed and the heat transfer and temperature of the heat pipe section. However, what the designer should watch for is the value of the mass calculated by the program. It should be decreasing throughout the program calculations. If it does not, or if the artificial value of 1E8 does not change, the user will have to change the range of the optimizing variable for the program calculations.

## 5.0 BASIC INFORMATION, POINTERS, AND GUIDANCE

### 5.0.1 BASIC INFORMATION

This section is intended to provide some basic information and guidance for use of this program.

The code is currently on the NASA Lewis VAX system. It is hoped to have a floppy disk copy of the program attached (see section 6.0) to the original of this document in order to make the program accessible to more users. If this is not the case, K. Baker of NASA Lewis has access to the program for those interested.

Note, as the code currently stands in the author's personal directory, it is named OPT not HEPSPARC for those who wish to simply copy it directly on the NASA VAX system.

In the event a floppy disk copy is available, it needs to be uploaded to a VAX system with an IMSL subroutine library available. At that time, or if it is desired to modify this program for some specific use, it will have to be re-compiled with the following commands:

```
FORTRAN/CONTINUATIONS=50 HEPSPARC.FOR
```

The continuations specification is required due to the presence of the "look-up" tables for the fin and heat pipe surface efficiencies. It must be linked with the IMSL information:

```
LINK HEPSPARC,IMSL
```

And finally, it may then be run by using:

```
RUN HEPSPARC
```

### 5.0.2 POINTERS AND GUIDANCE

As mentioned previously, it is highly recommended that all data decks be created with the interactive usage of the program. It is anticipated a design will progress by a systematic variation of variables associated with a baseline design. Therefore, if the data deck is initially created, then it can be easily, progressively, modified to close in on a final design. Also, it is suggested to use the optimizing option of the program initially to narrow the design possibilities. Then, for the detailed analysis, the non-optimizing version of the code can be used to obtain a slightly more refined analysis. Experience has shown this method not only saves design time, it also saves computer time. This last fact is especially true when very large radiator systems (on the order of megawatts) are being designed and analyzed.

One last point to be made is some advice on how to interpret the various parameters associated with a radiator design and how they are referred to in this code. This code was initially written to help analyze and validate the

design of the SP-100 heat pipe radiator. Many of the options and methods are based on that initial work. Therefore, it is recommended that the user, if they are already familiar with the SP-100 radiator, keep it in mind as this program is being used. If the user is not familiar with the particular design, it will not be a detriment to the use of this code, and this manual, as it stands, is sufficient to provide the information required for the design and analysis of a coupled pumped loop/heat pipe radiator system

### 5.1 CONCLUDING REMARKS

This manual is intended to be a guide to the use of the HEPSPARC program. It has outlined the basic applicability of the design code as well as provided detailed information concerning the workings of the code and in particular how the code should be used.

Many areas have already been identified as places that need improvement and implementation into the code. Among these are the incorporation of bumping information, and the incorporation of impact coefficients for some materials for which data is not available. Also, the optimizing version of the code can be improved to provide more choices for the variable being optimized as well as finish all aspects of the choices that are currently identified as being available (e.g. finish the heat pipe diameter variable to allow wicks other than grooves to be used in the design). It is also hoped to expand the materials library to offer additional choices for design situations.

It is hoped this manual is sufficiently clear to allow the new user to make viable use of the HEPSPARC code. Similar information of different detail level has been purposely provided in different areas of the manual to provide for those readers of varying interest levels to obtain what they may be looking for in one place. Any suggestions for the improvement of this manual or to the computer code itself would be greatly appreciated and considered.

6.0 CODE LISTING

A Copy of the Fortran Source Code or the Executable Image  
Can Be Requested By Contacting :

Karl W. Baker  
National Aeronautics and Space Administration  
Lewis Research Center  
Solar Dynamics and Thermal Systems Branch  
21000 Brookpark Road  
Cleveland, Ohio 44135  
(216) 433-5278

## 6.1 LIST OF SUBROUTINES

The subroutines currently used in the HEPSPARC program are listed below along with a short synopsis of the section's purpose and working. This list serves as a quick reference to the user for determination of the intended function of the various routines used. The subroutines are listed in alphabetical order for ease of use of the section.

<u>Subroutine or function name</u>	<u>Purpose</u>
...PAT	The ... stands for a set of three letters (LIT:lithium, NAK:sodium/potassium, HEL:Helium, TOL:toluene, POT:potassium, SOD:sodium, WAT:water, CES:cesium, MER:mercury, MET:methane, FRE:freon-11, NHE:Heptane, DOW: Dowtherm A, and AMM:Ammonia) to represent subroutines that determine the compatibility of the working fluids with the various containment envelope materials for the heat pipes and transport ducts.
XXXXXX	Subroutines LITH(lithium), HEL(helium), TOUL(toluene), POT(potassium), SOD(sodium), CES(cesium), WATER(water), HG(mercury), METH(methane), FREON(Freon-A), NHEP(n-heptane), DOWTHM(Dowtherm-a), AMMON(ammonia), STAIN(stainless steel), TITA(titanium), BERYL(beryllium), ALUM(aluminum), MAGN (manesium-lithium), NIOB(niobium), IRON(carbon-steel), NICKEL(nickel), COPPER(copper), TUNGS(tungsten), INCONN(Inconel), MOLY(molybdenum), and TANT(tantalum), are all used to establish temperature dependent properties for the various materials needed in the radiator design.
ACHANGE	This subroutine determines the change in the heat pipe vapor Mach number and other properties between the evaporator and condenser regions when a different wick structure is used in the two areas.
ARMOR	This routine controls the code structure for determining the required armor thickness of the heat pipes and transport ducts. Various areas, fluxes, and thickness are determined based on geometrical and modeling flags passed to the routine.
BLOCK DATA EFFICIENCY	This block contains the information needed for the determination of the fin and surface efficiencies.
BLOCK DATA FLUID	This data block that contains information required to determine some of the thermal properties of lithium, potassium, and sodium for use in the heat pipe heat transfer calculations.
BRENT	This function is part of the actual minimization algorithm. This subroutine finds the actual minimum mass value of the radiator after MNBRAK has bracketed the value. This routine was taken from

Reference 17 and modified for use here.

CAPLIM This routine determines the capillary limit of the heat pipe in question.

CAPOUT This routine establishes key words for the compatibility determination of the fluids and materials.

CHECK This routine contains the control structure to determine the compatibility of the working fluids and container materials.

COMPF This computes fitted thermal functions for use with the FLUID BLOCK DATA information.

DEBRIS This establishes a guess at the maximum thickness of armor required when a space debris flux is used for a radiator design.

DIAVAR This subroutine establishes the parameters of the heat pipe during the optimization design option using the heat pipe diameter as the parameter. More than just the diameter needs to be varied for this type of analysis, and this algorithm accounts for changes in the wick and internal structure of the heat pipe as the outside diameter is changed.

DINTER This function supports the EFFS routine. It interpolates values of the fin and surface data and also does some error checking.

DPLIQ This subroutine calculates the pressure drop experienced by the fluid contained in the wick structure of the heat pipe. It is used in the determination of the limits of the heat pipes.

DPVAP This routine contains the control structure for determination of the vapor pressure drop in the heat pipe evaporator and condenser.

DPVC This subroutine calculates the pressure drop experienced by the vapor in the condenser section of the heat pipe. This is used in the determination of heat transfer and fluid dynamics of the heat pipe.

DPVE This subroutine calculates the pressure drop experienced by the vapor in the evaporator section of the heat pipe. This is used in the determination of heat transfer and fluid dynamics of the heat pipe.

EFFS This routine calculates the fin and surface efficiency of the heat pipe and fin combination based on material and geometric specifications.

FACT This routine is not currently used by the program but has not been removed from the source code.

**FINDT** This routine determines the saturation temperature of the fluid and vapor based on its pressure within the heat pipe. It is used in the determination of the heat transfer characteristics of the system.

**FLUX** This subroutine establishes the actual flux (micro-meteoroid and space debris) present for the armor determination.

**FRIC** This subroutine calculates the friction factor required for the determination of the pressure drop of the fluid in the transport duct.

**FUNC** This subroutine contains the control structure for calculating the radiator characteristics during the mass minimization option of the design algorithm. Allowable temperature drops in a radiator section are established, and record keeping is done concerning the heat transfer characteristics of the design.

**GROOVE** This subroutine determines the hydrodynamic and thermal properties of the groove wick that will be used in the heat transfer calculations.

**HEADER** This subroutine calculates the heat transfer that occurs from the transport duct of the radiator. The header length is considered to be only that length of the transport duct that has heat pipes on or in it.

**HEAT** This routine contains the control structure for determination of the heat transfer of the system. Calculations are done to determine the required number of heat pipes in a system as well as temperatures for changing to different heat pipe fluids during the analysis.

**HP** This subroutine calculates the heat transfer capabilities of the heat pipe from the transport duct to the outside of the heat pipe. This is compared to the heat transfer determined from QSHP, and temperatures are modified as needed to balance these values.

**HP1** This routine establishes the choices of possible heat pipe fluids for a given temperature. This routine is used multiple times in the interactive input option when the design requires more than one the heat pipe working fluid to cover the range of temperatures of the system.

**HPM** Information concerning the physical details of each heat pipe are obtained in HPM during interactive input. This also has control structure to call other subroutines to obtain all the data to characterize the heat pipes.

**HTC** This subroutine determines the convective heat transfer coefficient of the fluid within the transport duct.

**INPUT** This subroutine carries out the majority of the interactive input of the program as well as control structure for the remaining interactive input. Also, establishment of the saved data file name is done here as well as some incidental calculations and flag setting.

**INRDWT** This routine contains the control structure used to read and write user specified input data and wick data. The input, or read option of this program is employed when non-interactive input is used.

**JOINT** This subroutine calculates the heat transfer that occurs from what is referred to as a joint section of the transport duct. It is the length between radiator panels that is considered to be inlet or outlet regions of the transport duct for each panel.

**LIMITS** This subroutine calculates the various limits of the heat pipes and determines if they are being violated in the radiator design.

**MAIN** This is the main control structure of the entire program. The non-optimized code calculation method is performed here. Also, non-interactive data reading takes place in MAIN.

**MASS** This routine calculates all the required masses of the radiator system. Both transport duct and heat pipe fluid and material masses are determined.

**MAT** This subroutine controls the determination of the properties for the fluids and metals in the system. It contains control structure need for establishing the correct material property for the heat pipes and transport duct fluids and materials.

**MAT1** This determines control of the selection of metal choices for the radiator design. It is used for transport duct and heat pipe liner and armor materials in the interactive input option of the program.

**MAT2** This determines control of the selection of fluid choices for the radiator design. It is used for both the transport duct and heat pipes in the interactive input procedure.

**MNBRAK** This routine is part of the actual minimization algorithm. This subroutine brackets the minimum value for Brent's method of optimization (BRENT). This routine was taken from Reference 17 and modified for use here.

**OPTIM** This routine contains the control structure for establishing the correct limits for the optimization program for as many times (i.e. several different heat pipe types) as is going to be required in the program.

**OUTPUT** This subroutine prints all the final output of the program. Some

calculations, such as pressure drop and specific mass and power values, are done within this routine to provide the final specifications of the radiator design.

- PROPTH This subroutine determines thermodynamic properties of the heat pipe fluid vapor stage for use in determining the heat transfer resistance in that section of the heat pipe.
- QSHP This function determines the heat transfer from the outside of a heat pipe with a fin attached to it based on assumed temperatures and emissivities. This heat transfer is compared to the heat transfer calculated in HP to equate the heat transfer.
- SCREEN This subroutine determines the hydrodynamic and thermal properties of the screen wick (with and without arteries) that will be used in the heat transfer calculations.
- SINTER This subroutine determines the hydrodynamic and thermal properties of the sintered metal wick (with and without arteries) that will be used in the heat transfer calculations.
- SOLVE This routine is used by ARMOR. It actually calculates the armor thickness of materials depending on various flags, geometrical parameters, survival requirements, and redundancies. An IMSL routine is used in order to calculate the value of a Poisson distribution in the routine.
- SOMETH Determines thermal resistance of the actual heat pipe vapor.
- SUBSTR This routine calculates the hoop stress that is present in the heat pipes and transport ducts.
- THERTB2 This routine determines the condensate state point for the heat pipe fluid.
- USER This subroutine is used during the interactive input option to prompt the code user for material properties when the choice is made to specify a material that is not available in the built-in materials library.
- VAPRES This subroutine determines the resistance to heat transfer generated by the vapor when it evaporates and condenses.
- WICK This routine obtains the physical and hydraulic characteristics of the heat pipe wicks during the interactive input.
- WIKTHR This subroutine contains the control structure for determination of the thermal and hydrodynamic characteristics of the heat pipe wick structure.
- WIKWAT This routine determines the mass of the wick in the heat pipe as well as other information needed to determine the heat pipe mass.

WKRDT

This routine actually reads and writes the wick data. The read option of this subroutine is employed when non-interactive input is used.

## 7.0 REFERENCES

1. Howell, H.R., et al, "Qualification of the Space Shuttle Orbiter Radiator System", Society of Automotive Engineers Paper No. 820886 (July, 1982)
2. Stipandic, E.A., "Spacecraft Application of Heat Pipes", American Institute of Aeronautics and Astronautics Paper No. 76-241 (April, 1976)
3. Presler, A.F., et al, "Liquid Droplet Radiator Program at the NASA Lewis Research Center", National Aeronautics and Space Administration Report No. TM 87139 (June, 1986)
4. White, K.A., "Moving Belt Radiator Technology Issues", Proceedings of the 23rd Intersociety Energy Conversion Engineering Conference, Paper No. 889132, (July, 1988)
5. Carelli, M.D., et al, "The Curie Point Radiator", Proceedings from the Fifth Symposium on Space Nuclear Power Systems (January, 1988)
6. Fraas, A. P., "Protection of Spacecraft from Meteoroids and Orbital Debris", Oak Ridge National Laboratory Report No. TM-9904 (March, 1986)
7. Lundberg, L. B., et al., "Hypervelocity Impact Studies on Titanium, Titanium Alloys, and Beryllium", Los Alamos National Laboratory Report No. LA-9417-MS (August, 1982)
8. Frost, V.C., "Meteoroid Damage Assessment", National Aeronautics and Space Administration Report No. NASA SP-8042 (May, 1970)
9. Baker, K.W., Tower, L.K., "The NASA Lewis Heat Pipe Code with Application to SP-100 GES Heat Pipes", Proceedings from the Fifth Symposium on Space Nuclear Power Systems (January, 1988)
10. Heat Pipes, Third Edition, Dunn, P.D., Reay, D.A. Pergamon Press, 1982.
11. Heat Pipe Design Handbook, B & K Engineering, 1981.
12. Fundamentals of Heat Transfer, Incropera, F. , DeWitt, J., Wiley Publishing Co., 1981.
13. Eckart, R., Kays, R., "Radiation Interaction Between a Cylindrically Finned Surface", ASME Proceedings, 1949.
14. M.J. Schor, "Micro-meteoroids and Space Debris Protection", General Electric Program Information Release No. U-1810-P2-448, April 1988.
15. N. Elfer, G. Kovacevic, "Design for Space Debris Protection", 3rd Annual American Institute of Aeronautics and Astronautics Greater New Orleans Symposium, November, 1985.

16. Handbook of Heat Transfer Fundamentals, Third Edition, Rosenhow, M. editor, McGraw Hill Publishing Co., 1986.
17. Numerical Recipes - The Art Of Scientific Computing, Press, W.H., et. al., Cambridge University Press, 1986.



# Report Documentation Page

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				15. Supplementary Notes Project Manager, James Calogeras, Power Technology Division, NASA Lewis Research Center, (216) 433-5278. A floppy diskette with a copy of the Fortran source codes or the Executable Image of HEPSPARC can be obtained by contacting Karl W. Baker, NASA Lewis Research Center, 21000 Brookpark Road, Cleveland, Ohio 44135, (216) 433-5278.	
16. Abstract A new computer code has been written for the NASA Lewis Research Center named HEPSPARC (which stands for HEat Pipe SPace Radiator Code). This code is used for the design and analysis of a radiator that is constructed from a pumped fluid loop that transfers heat to the evaporative section of heat pipes. This manual is designed to familiarize the user with this new code and to serve as a reference for its use. This manual documents the work done thus far. It is also intended to be the first step towards verification of the HEPSPARC code. Details are furnished to provide a description of all the requirements and variables used in the design and analysis of a combined pumped loop/heat pipe radiator system. A description of the subroutines used in the program is furnished for those interested in understanding its detailed workings.					
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